Directed Energy Missile Defense in Space

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Directed Energy Missile Defense in Space

Background Paper

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Preface

This background paper was prepared by Dr. Ashton B. Carter under a contract with the Office of Technology Assessment. OTA commissions and publishes such background papers from time to time in order to bring OTA up to date on technologies that are the subject of frequent congressional inquiry. After Dr. Carter's work was under way, Senators Larry Pressler and Paul Tsongas of the Senate Foreign Relations Committee requested that the resulting paper be made available to that Committee as soon as possible. OTA is issuing the paper in the belief that others in Congress and members of the public will find it of interest and importance.

An OTA background paper differs from a full-fledged technology assessment. Background papers generally support an ongoing assessment of broader scope or explore emerging technological issues to determine if they merit a fuller, more detailed assessment. On March 22, 1984, the Technology Assessment Board directed OTA to carry out a full-fledged assessment of "New Ballistic Missile Defense Technologies, " for which this background paper will serve as one point of departure.

This paper was prepared for OTA's International Security and Commerce Program, under the direction of Lionel S. Johns (Assistant Director, Energy, Materials, and international Security Division) and Peter Sharfman (Program Manager).

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INTRODUCTION

Section 1
INTRODUCTION

This Background Paper describes and assesses current concepts for directed-energy ballistic missile defense in space. Its purpose is to provide Members of Congress, their staffs, and the public with a readable introduction to the so-called "Star Wars" technologies that some suggest might form the basis of a future nationwide defense against Soviet nuclear ballistic missiles. Since these technologies are a relatively new focus for U.S. missile defense efforts, little information about them has been readily available outside the expert community.

Directed-energy or "beam" weapons comprise chemical lasers, excimer and free electron lasers, nuclear bomb-powered x-ray lasers, neutral and charged particle beams, kinetic energy weapons, and microwave weapons. In addition to describing these devices, this Background Paper assesses he prospects for fashioning from such weapons robust and reliable wartime defense system esistant to Soviet countermeasures. The assessment distinguishes the prospects for perfect or ear-perfect protection of U.S. cities and populaon from the prospects that technology will chieve a modest, less-than-perfect level of performance that will nonetheless be seen by some xperts as having strategic value. Though the focus is technical, the Paper also discusses, but oes not assess in detail, the strategic and arms ontrol implications of a major U.S. move to develop and deploy ballistic missile defense (BMD).[1]

This Background Paper grows indirectly out of resident Reagan's celebrated television speech f March 23, 1983, in which he called for a "longerm research and development program to begin to achieve our ultimate goal of eliminating the threat posed by strategic nuclear missiles. "[2] Pursuant to the President's speech, the Department of Defense established a Defensive Technologies Study Team under James C. Fletcher (of the University of Pittsburgh) to prescribe a plan for the R&D program. A parallel effort, called the Future Security Strategy Study and headed by Fred S. Hoffman (of Research and Development Associates), addressed the implications for nuclear policy of renewed emphasis on BMD. This Paper covers the same technologies and issues as these Defense Department studies. The ABM Treaty reached at SALT I[3] severely restricts the development, testing, and deployment of BMD systems. Though this Background Paper treats the strategic roles of missile defenses, including many of their arms control implications, it does not treat the vital international political implications of a major U.S. move to BMD.

Focused on directed-energy intercept of missiles in their boost phase, i.e., on "Star Wars" proper, this paper does not analyze midcourse and reentry BMD systems or non-BMD applications of directed-energy weapons.[4] "Star Wars" efforts generally further concentrate on intercept of intercontinental ballistic missiles (ICBMs) rather than the related but somewhat different problems of intercept of submarine launched ballistic missiles (SLBMs) or intermediate-range ballistic missiles (IRBMs). This Paper is therefore not a substitute for a more complete treatment of the entire subject of BMD.[5] Moreover, BMD itself is only part of the larger subject of strategic defense, comprising defense against bombers and cruise missiles, civil defense, passive defense of military targets, anti-submarine warfare (ASW), and preemptive counterforce attack in addition to BMD.

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[1] BMD is the most common of four roughly equivalent acronyms vering defense against nuclear ballistic missiles. Such defenses ere formerly called anti-ballistic missile (ABM) systems, but this signation fell out of favor after the debate over and eventual dese of the Sentinel and Safeguard ABM systems in the late 1960's d early 1970's. BMD largely replaced ABM as the term of choice, t recently the more self-explanatory Defense Against Ballistic ssiles (DABM) has gained popularity. Within the Executive anch BMD efforts pursuant to President Reagan's so-called "Star ars" speech are referred to as the Strategic Defense Initiative (SDI). rmally the term strategic defense comprehends other methods limiting damage from nuclear attack besides BMD.

[2] The relevant portions of President Reagan's speech are reproduced in Appendix A.

[3] The ABM Treaty and related documents are reproduced in Appendix B.

[4] Appendix C describes briefly, but does not assess, other proposed military applications of directed-energy weapons.

[5] For a more complete treatment, see *Ballistic Missile Defense*, ed. Ashton B. Carter and David N. Schwartz (Brookings, 1984).

It is unusual for the President to express himself on, and for the Congress and public consequently to concern themselves with, long-term research and development. "Star Wars" is thus a somewhat unusual subject for a technology assessment intended for a public policy audience. It is in the nature of this subject that unknown or unspecified factors outweigh what is known or can be presented in concrete detail. Many of the technologies discussed in this Paper, and most certainly all of the schemes for fashioning a defense system from these technologies, are today only paper concepts. In the debate over the Safeguard ABM system a decade ago, or over basing modes for the MX missile in recent years, one could analyze in detail the technical properties of well-defined systems in engineering development. So vague and tentative are today's concepts for "Star Wars" BMD that a comparable level of analysis is impossible. Fashions and "front runners" are likely to change, Nonetheless, one is faced with assessing the concepts receiving attention today within the Executive Branch and which underlie the President's Strategic Defense Initiative. Fortunately, judgments deduced from generic properties of these concepts, which are unlikely to change, are sometimes telling.

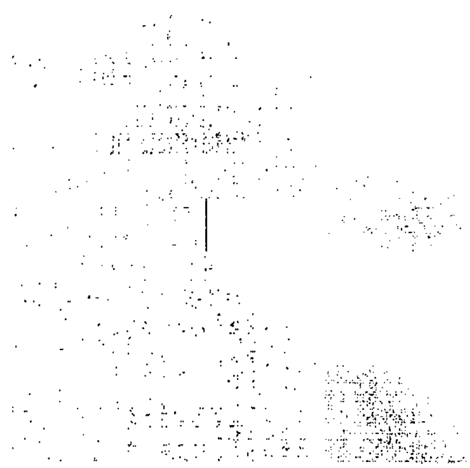
This Paper is based on full access to classified information and studies performed for the Executive Branch. But it turns out that a fully adequate picture of this subject can be presented in unclassified form. One reason is that the important features of the directed-energy BMD concepts are based on well-known physics, and many have in fact been discussed for 20 years. The second reason is that at this early stage of conceptualize tion there is simply no point in (and little basis for) discussion at the detailed level where classified particulars make a difference. The properties of actual weapon systems in engineering devel opment, by contrast, are normally and under standably classified.

The author and OTA wish to thank officials o the Army's Ballistic Missile Defense Systems Corn mand (BMDSCOM), the Lawrence Livermore Na tional Laboratory, the Los Alamos Nationa Laboratory, the Defense Advanced Research Proj ects Agency (DARPA), the Sandia National Labo ratory, the Air Force Weapons Laboratory (AFWL) the Office of the Secretary of Defense (OSD), and the Central Intelligence Agency (CIA) for thei hospitality and cooperation. Many individual aided the research for this Background Paper though none shares the author's sole respons bility for errors of fact or judgment. The author and OTA wish especially to thank Hans Bethe Richard Briggs, Al Carmichael, Albert Carnesale Paul Chrzanowski, Robert Clem, Sidney D. Drel Dick Fisher, John Gardner, Richard L. Garwir Ed Gerry, Jack Kalish, Glenn A. Kent, Louis Ma quet, Michael M. May, Tom Perdue, Theodor A. Postol, George Rathjens, Victor Reis, Jac Ruina, George Schneiter, David N. Schwartz Robert Selden, Leon Sloss, Daryl Spreen, Robi Staffin, John Steinbruner, Sayre Stevens, Thomas Weaver, Stephen Weiner, and Wayne Winter

This Background Paper contains information current as of January 1, 1984.

Section 2

BOOSTER CHARACTERISTICS



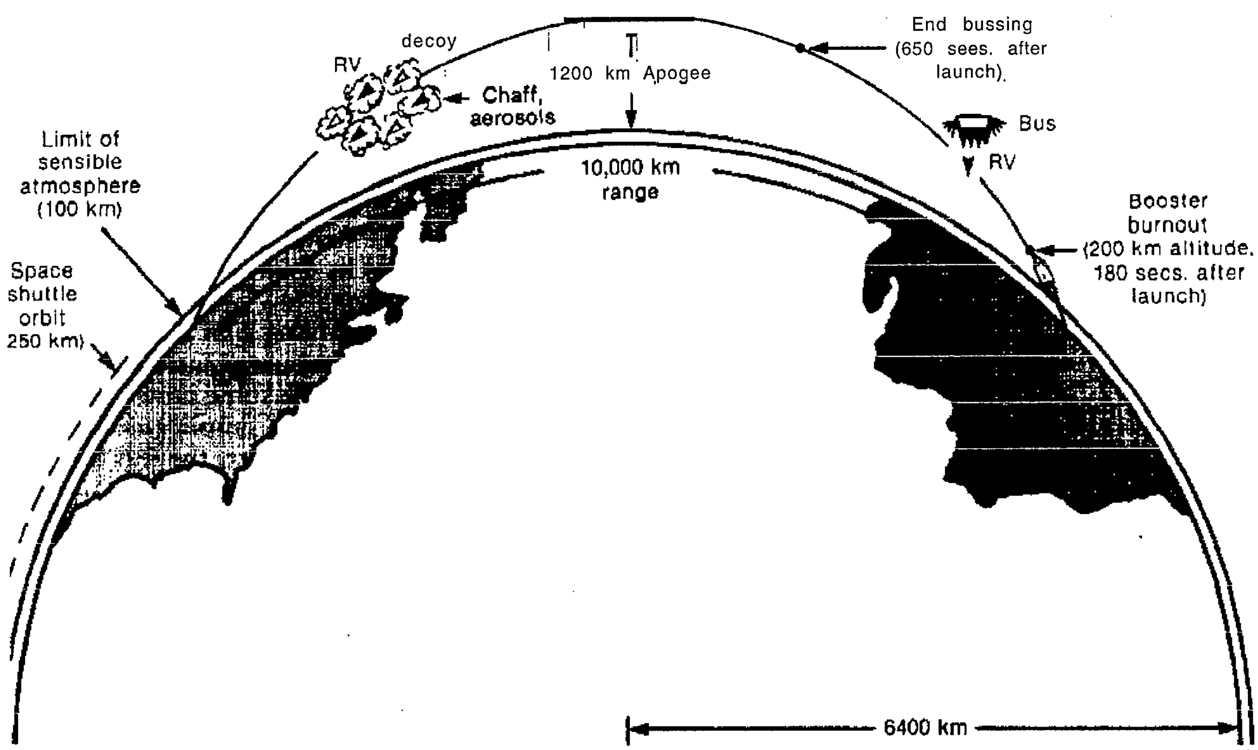
Section 2
BOOSTER CHARACTERISTICS

Intercept of ICBMs in their boost phase offers advantages and disadvantages relative to intercept of reentry vehicles (RVs) later in the trajectory. The boosters are fewer and generally more easily disrupted or destroyed than the RVs. Decoy boosters would have to match an ICBM's huge heat output, making this offensive tactic attractive only in certain circumstances. The disadvantages of boost phase intercept are that boost phase is only a few minutes long and comprises the earliest stage of an attack, and that sensing and intercept must be accomplished from outer Space and over enemy territory.

Figure 2.1 shows an ordinary (minimum energy) trajectory of a hypothetical future Soviet ICBM hat has been given, for illustration, the boost profile of the U.S. MX Peacekeeper. Pressure from a steam generator expel Is the missile from its storage cannister. Once clear of the cannister, the missile ignites its first stage motor. The first stage burns for about 55 seconds, burning out at an altitude of about 22 kilometers. The second stage also burns for 55 see, burning out at 82 km. The third stage burns for 60 sec and carries the remainder of the missile to about 200 km, the altitude of the lowest earth orbiting satellites.

When the third stage is jettisoned at the end of the 3-minute boost phase, the remainder of the missile consists of the post-boost vehicle (PBV) or ''bus" and its cargo of 10 reentry vehicles. At this point the bus and RVs are in ballistic free-fall flight to the United States. Even if they are disrupted in some way or destroyed, these objects or their debris will reenter the atmosphere over the United States. The last few seconds of third stage burn are crucial for giving the payload

Figure 2.1 .–The Flight of a Hypothetical Future Soviet ICBM With the Booster Characteristics of the U.S. MX Peacekeeper, Drawn to Scale



SOURCE: Author

enough speed to reach the United States, so disruption of boost phase any time right up to burnout will cause the warheads to fall far short.

For the next 500 seconds or so after burnout—almost until it reaches apogee—the bus uses its thrusters to make small adjustments to its trajectory. After each adjustment, it releases an RV. RVs released on different trajectories continue on to different targets as multiple independently targeted reentry vehicles (MIRVs). Decoys and other penetration aids for helping the RVs escape defenses later in the trajectory are deployed during busing.

The bus itself is a target of declining value as it dispenses its RVs. Destroying it early in the deployment process would obviously be useful: the RVs not yet deployed from the bus would still arrive at the United States, but perhaps nowhere near their intended targets. If cities are the targets, relatively small aiming errors might be inconsequential. In any event, tracking the bus to allow some form of intercept requires a different type of sensor from that which tracks the booster for boost phase intercept, since the bus's thrusters are small and operate intermittently. Because of its small size, the bus (or at least critical elements of it) might be more easily hardened against directed-energy weapons than the booster. For all these reasons, the value of attempting bus intercept is very unclear, and it usually does not figure prominently in BMD discussions.

From apogee, the slowest point in their free-fall trajectory, the RVs and empty bus gain speed as they fall back to earth. RVs are more resistant to damage from directed-energy weapons than boosters, and they might be accompanied by many decoys. When these objects enter the upper atmosphere at about 100 km altitude somewhat over 2 minutes before impact, they begin to heat up, and the lighter objects slow down. Still lower, below 50 km altitude and less than a minute before impact, the objects undergo violent deceleration and the bus breaks up. The RVs, now glowing with heat, streak toward their targets at an angle of about 23 degrees to the horizontal.

The trajectory shape can be altered at the expense of payload (see Figure 2.2). A lofted trajectory takes longer but reenters faster, and a depressed trajectory can offer unfavorable viewing angles to defensive sensors late in the trajectory.

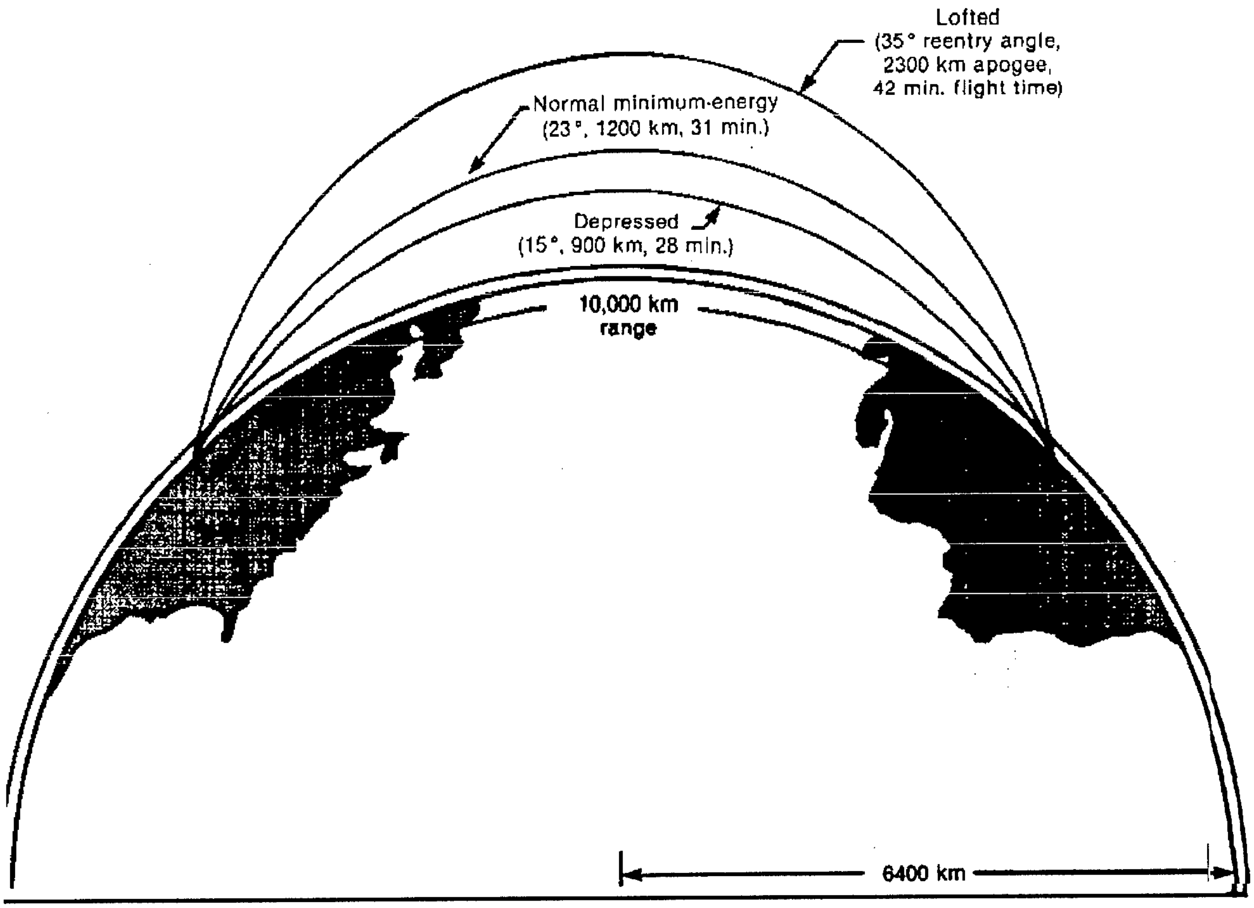
The most important trajectory variations from the point of view of boost phase intercept are variations in boost profile. Boosters like MX were designed with no regard for boost phase BMD, and optimizing their design gave rise to rather long boost times. But boost phase can be shortened–giving less time for boost phase weapons to act–and accomplished within the atmosphere—where certain directed-energy weapons cannot penetrate–with relatively little reduction in payload or increase in missile size. Fast burn is accomplished most easily with solid-fueled rockets. Liquid-fueled boosters like the Soviet SS-18s and SS-19s burn more slowly and burn out at higher altitudes. Thus while MX burns out at 200 km after 3 minutes of boost, the SS-18 burns out at 300-400 km after 5 minutes. The next generation of Soviet ICBMs will reportedly employ solid propellants.

Studies performed for the Defense Department showed that with a 25 percent reduction in payload, a booster about the same size as MX could be built which would burn out in less than 1 minute at only 80 to 90 km, well within the sensible atmosphere. At 90 km the atmosphere is still too dense for extremely accurate RV deployment or for deployment of lightweight RV decoys and other penetration aids aimed at later defensive layers: these functions require an additional 10 to 15 seconds of precision deployment between 90 and 110 km. If the offense needs precision accuracy for some of its ICBMs but fears intercept during these additional few seconds of high-altitude operation, mounting one or two RVs on each of several "microbuses" instead of all the RVs on a single bus affords some protection. Each microbus would contain a simple guidance system only good enough to carry the RVs from upper stage burnout to 110 km. Instead of presenting one target above 90 km, therefore, such a booster would present several targets.

The United States is studying a "Midgetman" missile endorsed by the President's Commission on Strategic Forces (the Scowcroft Commission

[1]"Short Burn Time ICBM Characteristic and Considerations," Martin Marietta Denver Aerospace, July 20, 1983 (UNCLASSIFIED).

Figure 2.2.—Normal (Minimum-Energy), Lofted, and Depressed ICBM Trajectories, Drawn to Scale



SOURCE : Author

with weight 15 to 25 percent that of MX and carying one warhead. Midgetman's warhead and ıus are combined i n one hardened structure. "able 2.1 shows the characteristics of Midgetman ariants designed to face a boost-phase intercept ystem. The fast-burn version burns out at 80 km fter 50 sees of boost. With a 10 percent increase 7 weight, the fast-burn version can carry a substantial payload of penetration aids. A low-flight-profile version is intended to stay within the atmosphere until burnout, protecting it from some types of directed-energy weapon. In the hardened version, one gram of ablative or other hielding material has been applied to each quare centimeter of the entire booster body (if ıe boost-phase intercept system did not begin operation until a minute or so after launch, the first stage might not have to be hardened). These mall boosters are all estimated to cost $10 to $15 million per copy, assuming a buy of 1,000 boosters. Costs for the second and subsequent thousand would of course be substantially smaller. These costs are two to three times higher per RV than MX.

The Soviet ICBM arsenal today comprises about 1,400 boosters, more than two-thirds of them MIRVd. Most are slow-burning liquid-fueled boosters. The U.S. arsenal contains about 1,000 faster-burning solid-fueled Minuteman boosters, about half of them MIRVd. Both sides are adding solid boosters to their arsenals in the 1980's.

The geographic distribution of offensive boosters can also be important to space-based boost-phase defenses. The number of satellites required in a defensive constellation usually increases if all opposing ICBM silos are concentrated in one region and decreases if the silos are spread over

Table 2.1.—ICBM Booster Characteristics

	Gross weight (kg)	Length (m)	Width (m)	Type	Booster burnout time (seconds after launch)	Booster burnout altitude (km)	End bussing time (seconds after launch)	End bussing altitude (km)	Comments
SS-18	220,000[a]	35.0	3.0	2-stage liquid	~300	~400	—	—	—
MX Peacekeeper	89,000	21.3	2.3	3-stage solid	180	200	650	1,100	Carries 10 RVs on a single bus
MIRVd fast-burn booster	87,000	22.9	2.1	2-stage solid	50	90	60	110	Deploys several "microbuses" carrying RVs and decoys
Midgetman	19,000	2.1	.5	2-stage solid	220	340	—	—	Carries one accurate RV
Midgetman fast-burn	20,000	13.8	5	2-stage solid	50	80	—	—	Carries one accurate RV
Midgetman fast-burn with midcourse penetration aids	22,000	4.3	1.5	2-stage solid	50	80		—	Carries one RV plus decoys
Midgetman with low flight profile	25,000	3.4	1.5	1st stage solid, 2nd liquid	220	100	—	—	Carries one accurate RV
Hardened Midgetman	30,000	15.1	1.5	1st stage solid, 2nd liquid	220	320	—	—	Carries one accurate RV; entire booster covered w th 1gm/cm² shielding
Pershing	7,500	10.5	0	2-stage solid	100	—	—	—	—

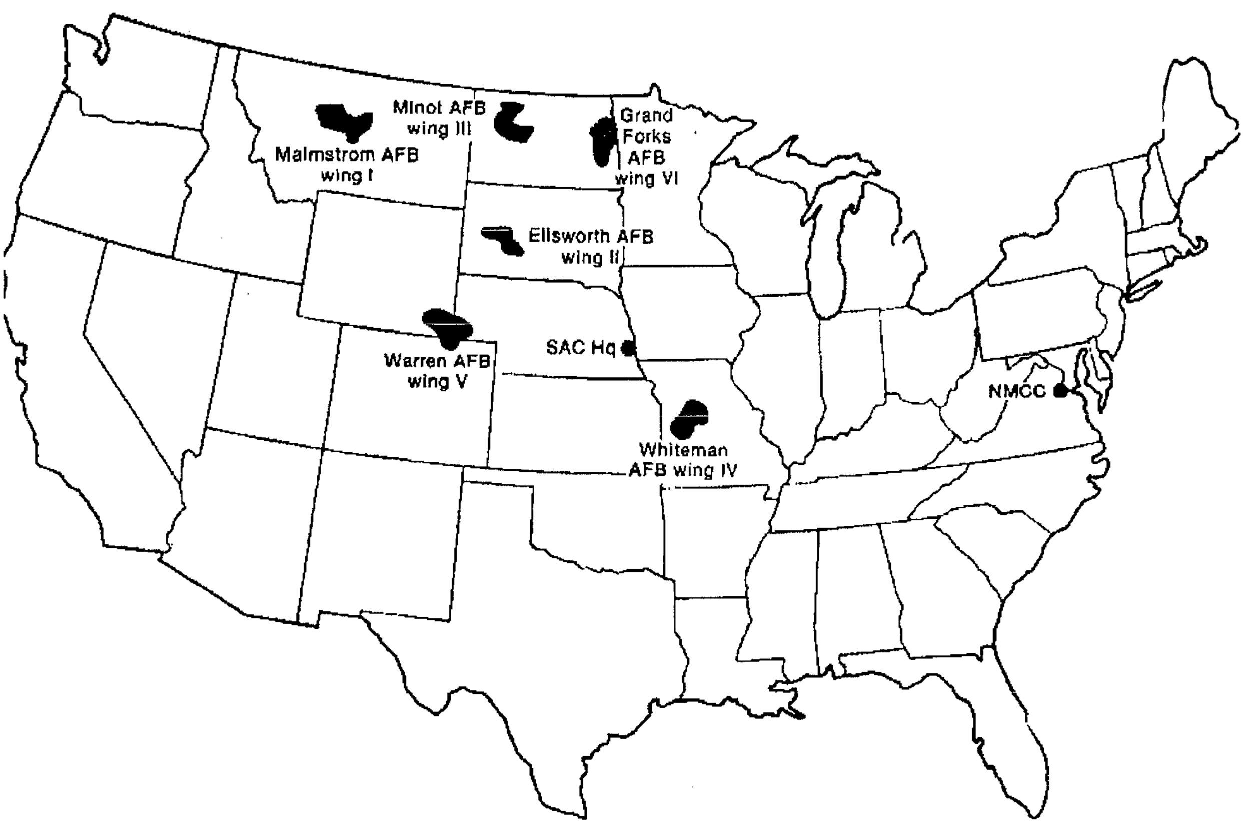
[a]*Soviet Space Programs 1976-1980* (Committee on Commerce, Science, and Transportation, U.S. Senate, December 1982). Part 1, p. 63.

SOURCE: Except where indicated, "Short Burn Time ICBM Characteristics and Considerations," and accompanying backup, presented to DTST, July 20, 1983, by Martin Marietta Denver Aerospace (UNCLASSIFIED).

wide land areas. (On the other hand, too much concentration allows defensive satellites to be focused on one region by choosing the orbits juviciously.) Soviet SS-18 ICBMs, their largest MIRVd missiles, are organized into 6 wings of about 50 missiles each, spread out over a large region of the U.S.S.R. U.S. Minuteman missiles are organized into 6 wings of about 150 missiles each. Figures 2.3 and 2.4 show the geographic distributions.

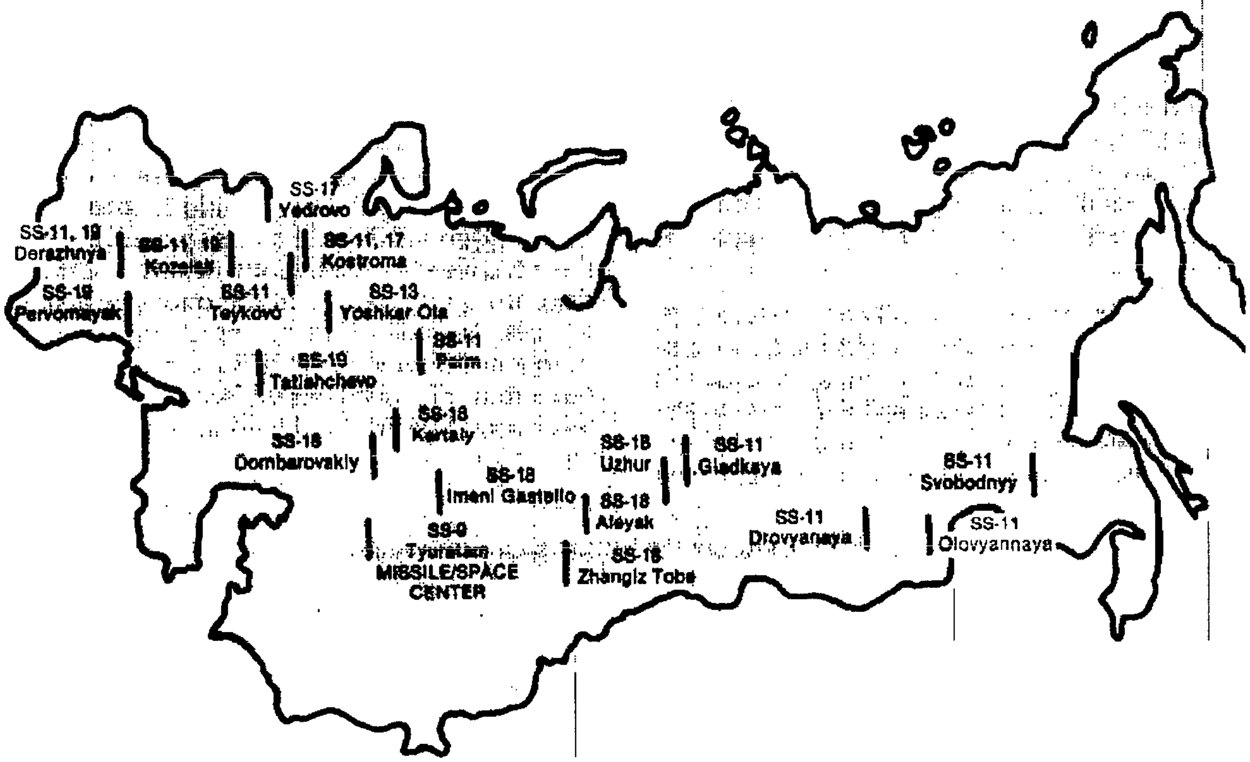
The capabilities of a hypothetical future U.S. BMD should be measured against the ***future*** and ***potential*** Soviet ICBM arsenal, not against today's arsenal. The future arsenal will differ due to the natural retirement of old ICBMs and introduction of new ones, and because the Soviets might well react with new and different deployments when they learn of any U.S. plans to deploy defenses. It is impossible to project Soviet deployments far into the future. A reasonable "baseline' estimate for the Soviet ICBM arsenal 15 to 20 years from now might assign them the same number of boosters they have today, but with burn characteristics similar to the U.S. solid-propellant MX. This Background Paper indicates where and how the effectiveness of a hypothetical U.S. defense depends on the nature of the offensive arsenal it faces. In addition to having shorter average burn times, future Soviet ICBMs could be more numerous, deployed less widely geographically, less highly MIRVd, hardened against intercept, and so on.

Figure 23.— Present U.S. ICBM Deployment **Areas**



SOURCE: OTA, MX Missile *Basing*, p *274*

Figure 2.4.—Present U.S.S.R. ICBM Deployment Areas



Type	ICBMs Number
Ss-11	550
SS-13	60
Ss-17	150
SS-18	308
SS-19	330
Total	1398

SOURCE: U.S. DOD Soviet Military Power, 2nd cd., p. 14.

Section 3

DIRECTED ENERGY WEAPONS FOR BOOST-PHASE INTERCEPT

Section 3

DIRECTED ENERGY WEAPONS FOR BOOST-PHASE INTERCEPT

This section describes the entire set of "beam weapons" being considered in the United States today for boost-phase ICBM intercept. Though these weapons receive the most attention, the "kill mechanism" that destroys the booster is not necessarily the most important or technically challenging part of an overall defense system. The next section describes other essential elements of a boost-phase defense.

A revisit to this subject several years from now might well find a new family of directed energy concepts receiving attention. But for now the devices described in this section are the basis for assessments of the prospects for efficient boost-phase defense, in the Defense Department and elsewhere (fig. 3.1). Though some of these concepts are new, many have in fact existed in one form or another for more than twenty years.

Figure 3. I

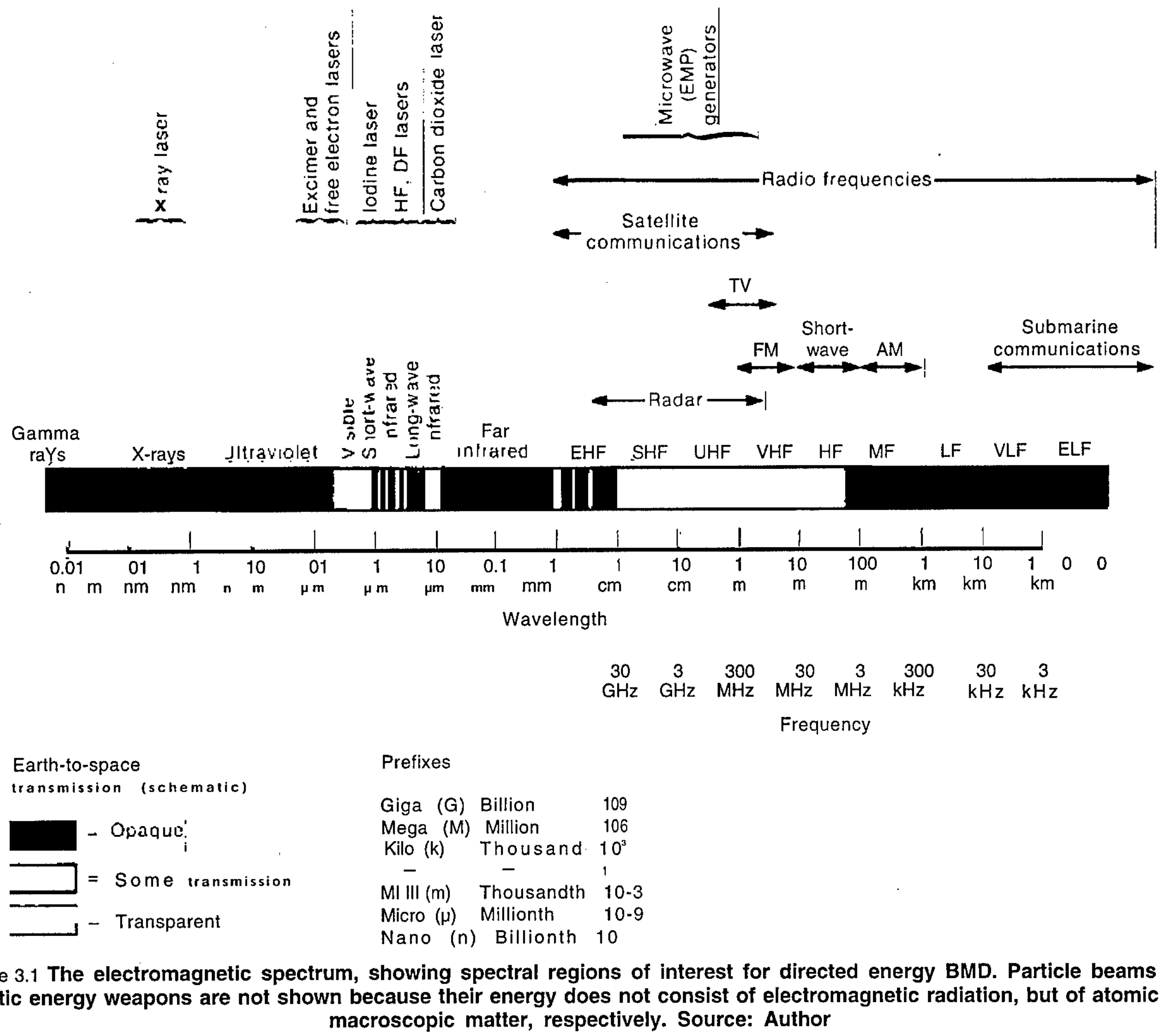


Figure 3.1 **The electromagnetic spectrum, showing spectral regions of interest for directed energy BMD. Particle beams and kinetic energy weapons are not shown because their energy does not consist of electromagnetic radiation, but of atomic and macroscopic matter, respectively. Source: Author**

For each concept this section attempts to work through, with some concreteness, the design of a hypothetical defensive system based on the concept. The resulting designs are **illustrative only;** no significance should be attached to precise numbers. Precision is simply not possible in the current state of technology and study of these concepts.

In all cases, the "current state of technology" (however this is defined in each case) is far from meeting the needs of truly efficient boost-phase intercept. The systems designed in this section illustrate the level to which technology would have to progress to be "in the ballpark." Much attention fastens on the gulf between the current state of technology and the ballpark requirements. This section does not emphasize such comparisons for several reasons. First, in some cases details of the precise status of U.S. research is classified. Second, and more importantly, quantitative comparisons (e.g., "A millionfold increase in brightness is required to fashion a weapon from today's laboratory **device") can mislead** unless accompanied by a deeper explanation of the technology; and the same quantitative measures are not appropriate for all technologies. Third, and most importantly, such comparisons imply that learning how to build the right device is tantamount to developing an efficient missile defense, which is far from true: equally crucial are design of a sensible system architecture, cost, survivability, resilience to countermeasures, and the myriad detailed limitations that do not turn up until later in development.

3.1 SPACE-BASED CHEMICAL LASERS: A FIRST EXAMPLE

This concept of directed energy weapon has been the one most frequently discussed in recent years for boost-phase ICBM intercept. For this reason (and not necessarily because it is the most plausible of all the concepts), it will be used to introduce certain features common to all the schemes that follow.

Making and Directing Laser Beams

A molecule stores energy in vibrations of its constituent atoms with respect to one another, in rotation of the molecule, and in the motions of the atomic electrons. The molecule sheds energy in the form of emitted light when it makes transitions from a higher-energy state to a lower-energy state. Lasing takes place when many molecules are in an upper state and few are in a lower state: one downward transition then stimulates others, which in turn stimulate yet more, and a cascade begins. The result is a powerful beam of light.

Energy must be supplied to the molecules to raise most of them to the upper state. This process is called pumping. In the case of the chemical lasers considered in this section, the pumping energy comes from the chemical reaction that makes the lasant molecules: hydrogen and fluorine react to form hydrogen fluoride (HF) molecules in an upper state. The other requirement for lasing–few molecules in the lower state–is satisfied simply by removing the molecules from the reaction chamber after they have made their transitions to the lower state and replacing them with freshly made upper state molecules. The pumping process is not perfect: not all the pumping energy ends up as laser light. The ratio of pumping energy in to laser energy out is called the efficiency of the laser.

Laser light is special in two respects: its frequency is precise, since all the light comes from the same transition in all the molecules; and the light waves from all the molecules emerge with crests and troughs aligned, since the waves are produced cooperatively. These special features make it possible to focus the laser energy with mirrors into narrow beams characterized by small divergence angles (see fig. 3.2). Nonetheless, there is a limit to the divergence angle that even a perfect laser with perfect mirrors can produce. The divergence angle (in radians) can be no smaller than about 1.2 times the wavelength of the light divided by the diameter of the mirror. Thus a laser with 1 micrometer (=1 micron)

Figure 3.2

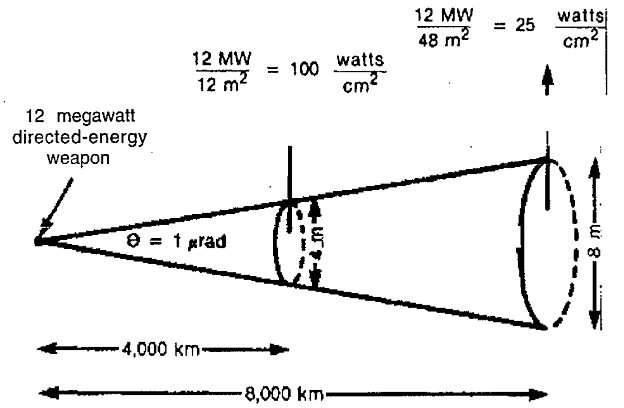


Figure 3.2 Basic power relationships for directed energy weapons. If the directed energy weapon has a divergence angle of 1 microradian, the spot size at a range of 4000 kilometers is 4 meters (12 feet). In this figure, the divergence angle is exaggerated about 1 million times. (For comparison of scale, the Earth's radius is about 6,400 km,) If the directed energy weapon emits 12 megawatts of power, a target within the spot at 4,000 km receives 100 watts on each square centimeter of its surface. (For comparison, 100 watts is the power of a lightbulb, and atypical commercial powerplant produces 1,000 megawatts). Since a watt of power equals one joule of energy per second this weapon would take 10 seconds to apply a kilojoule per square centimeter (1 KJ/cm²) to the target at 4,000 km range. Source: Author

wavelength projected with a 1 meter mirror could have at best a 1.2 microradian divergence angle, making a spot 1.2 meters wide at a range of 1,000 kilometers (refer to fig. 3.2).[1] This perfect performance is called the diffraction limit. Dividing the laser power output by the size of the cone into which it is directed (cone size is measured in units called steradians; a divergence angle of x radians results in a cone of size $\pi x^2/4$ steradians) yields the laser's "brightness," the basic measure of a weapon's lethality.

Destroying Boosters with Lasers

Assuming a high-energy laser with small divergence angle can be formed, stabilized **so it does** not wave about (jitter), and aimed accurately, what effect will it have on an ICBM booster? No clear answer to this question can be given without more study and testing. Estimates of the hardness achievable with future boosters are probably reliable within a factor of two or three, though estimates of the hardness of current Soviet boosters are probably reliable only to a factor of 10 or so.

Roughly speaking, laser light can damage boosters in two distinct ways. With moderate intensities and relatively long dwell times, the *laser* simply burns through the missile skin. This first mechanism is the relevant one for the chemical lasers described in this section. The second mechanism requires very high intensities but perhaps only one short pulse: the high intensity causes an explosion on and near the missile skin, and the shock from the explosion injures the booster. This mechanism, called impulse **kill, is** more complex than thermal kill and is less well understood. it will be discussed in the next section.

Bearing in mind the uncertainties in these estimates, especially the complex interaction of heating with the mechanical strains of boost, the following estimates are probably reliable: A solid-fueled booster can probably absorb without disruption up to about 10 kilojoules per square centimeter (kJ/cm²) on its skin if a modicum of care is taken in the booster's design to eliminate "Achilles' heels. " This energy fluence would result from 1 second of illumination at 10 kilowatts per square centimeter (kw/cm²), since one watt equals one joule per second.[2] Applying ablative (heatshield) material to the skin can probably double or triple the lethal fluence required. Applying a mirrored reflective coating to the booster is probably not a good idea, since abrasion during boost could cause it to lose its lustre. Spinning the booster triples its hardness, since a given spot on the side of the booster is then only illuminated about a third of the time.[3] On the other

[1] The spot from a perfect laser with perfect mirrors would actually be brighter at the center than at the edges. The full angle subtended by this spot (the Airy disk from null to null in the diffraction pattern) is 2.4 times the wavelength divided by the mirror diameter, but most of the energy is in the central fourth of this area: hence the use in the text of the multiplier 1.2.

[2] The lethal fluence (in kJ/cm²) must accumulate **over a** relatively short time, so that the booster wall suffers a high rate of heating. Thus a flux of 30 watts/cm² would deposit 10 kJ/cm² in 330 sec of dwell time, but such a slow rate of heating would probably not damage the booster.

[3] It is possible that uniform heating around the circu reference of the booster introduces lethal mechanisms distinct from those that apply to heating a single spot on the side of the booster. In that case, spinning the booster might not lengthen the required dwell time by the full amount dictated by geometry.

hand, currently deployed boosters, especially the large liquid Soviet SS-18s and SS-19s, might be vulnerable to I kJ/cm^2 or even less. These too could be hardened by applying heatshield material.

An Orbiting Chemical Laser Defense System

Consider a space-based BMD system comprised of 20-megawatt HF chemical lasers with 10 meter mirrors. The HF laser wavelength of 2.7 microns is attenuated as it propagates down into the atmosphere, but most of the light gets down to 10 km or so altitude. Deeper penetration is not really needed, since the laser would probably not be ready to attack ICBMs until after they had climbed to this altitude, and in any event clouds could obscure the booster below about 10 km. (Substituting the heavier and more expensive deuterium, an isotope of hydrogen, to make a DF laser at 3.8 micron wavelength would alleviate attenuation, but the longer wavelength would require larger mirrors.)

A perfect 10 meter mirror with a perfect HF laser beam yields 0.32 microradian divergence angle. The spot from the laser would be 1.3 meters (4,0 ft) in diameter at 4 megameters (4,000 kilometers) range. 20 megawatts distributed evenly over this spot would be an energy flux of 1.5 kw/cm^2. The spot would need to dwell on the target for 6.6 seconds to deposit the nominal lethal fluence of 10 kJ/cm^2. At 2 megameters (Mm) range, booster destruction would require only a fourth of this time, or 1.7 seconds of illumination. Since light takes about a hundredth of a second to travel 4 megameters and the booster is traveling a few kilometers per second, the booster moves about sO meters in the time it takes the laser light to reach it. The laser beam must therefore lead the target by this distance.

The next step is to choose orbits for the satellites so that the U.S.S.R.'s ICBM silos are covered at all times and so that there are enough satellites overhead to handle all 1,400 of the present Soviet booster population. Equatorial orbits (fig. 3.3) give no coverage of the northern latitudes where Soviet ICBMs are deployed. Polar orbits give good coverage of northern latitudes but concentrate satellites wastefully at the poles where there are no ICBMs. The optimum constellation consists

Figure 3.3

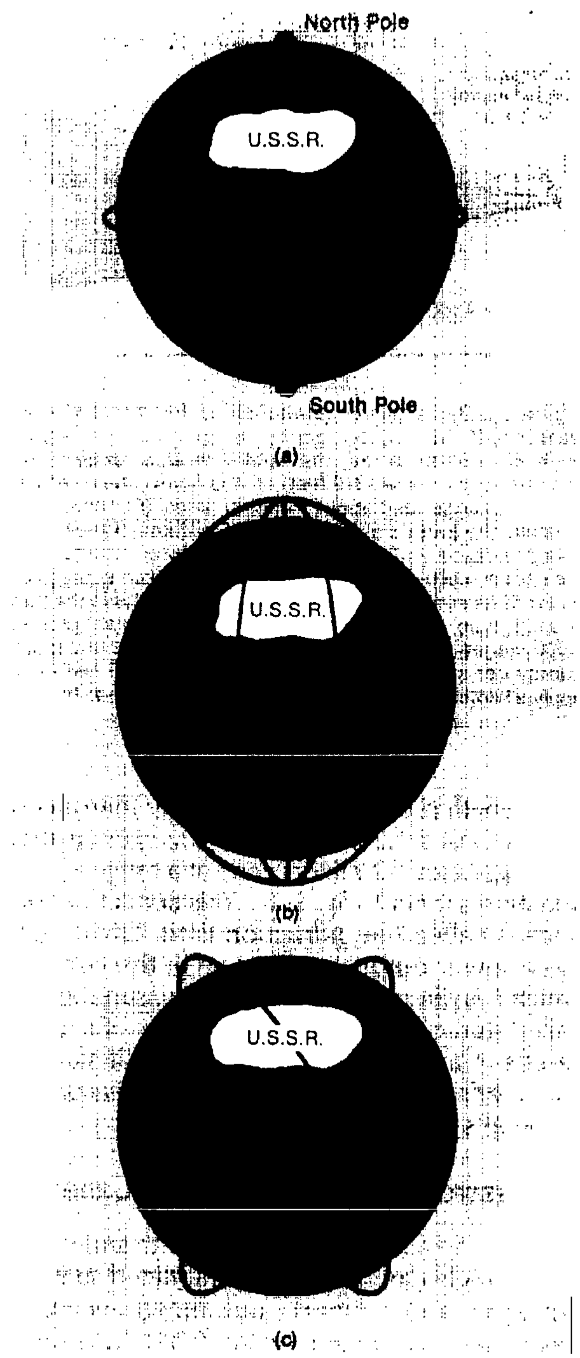


Figure 3.3 Designing a constellation of directed energy weapon satellites for optimum coverage of Soviet ICBM fields. Equatorial orbits (a) give no coverage of northern latitudes. Polar orbits (b) concentrate coverage at the north pole. Inclined orbits (c) are more economical. Slight additional economies are possible in some cases with further elaboration of the constellation design. Source: Author

of a number of orbital planes inclined about 70° to the equator, each containing several satellites.

The shorter the lethal range of the directed energy weapon, the lower and more numerous the satellites must be. For instance, with a lethal range of 3 Mm, 5 planes containing 8 satellites each, or a total of 40 satellites, are needed to ensure that Soviet boosters exiting Soviet airspace would be within lethal range of one satellite. If the lethal range is increased to 6 Mm, only 3 planes of 5 satellites each are needed. This dependence of constellation size on weapon range is displayed in figure 3.4. (It is possible to adjust these numbers a bit by using slightly elliptical orbits with apogees over the northern hemisphere, adjusting inclinations and phasing, etc.). In the present example, requiring that at least one HF laser be no further than 4 Mm from each Soviet ICBM site at all times (corresponding to no longer than 6.6 seconds dwell time per booster) results in the illustrative constellation of 32 orbital positions shown in figure 3.5.

Since the 1,400 Soviet boosters currently deployed are spread out over most of the Soviet Union, perhaps 3 of the 32 orbital positions would be over or near the Soviet Union at a time, able to make efficient intercepts. That is, only one in 11 deployed U.S. battle stations would participate in a defensive engagement. The ratio of the total number of battle stations on orbit to the number in position to participate **in a defensive engagement is called the absentee ratio.** The inevitable waste reflected in the absentee ratio—

Figure 3.4

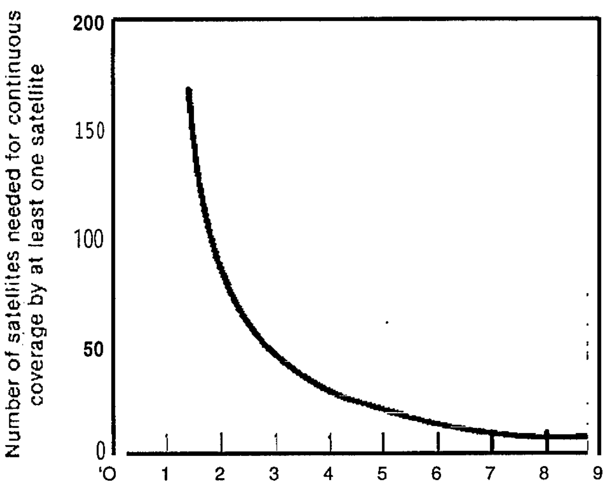
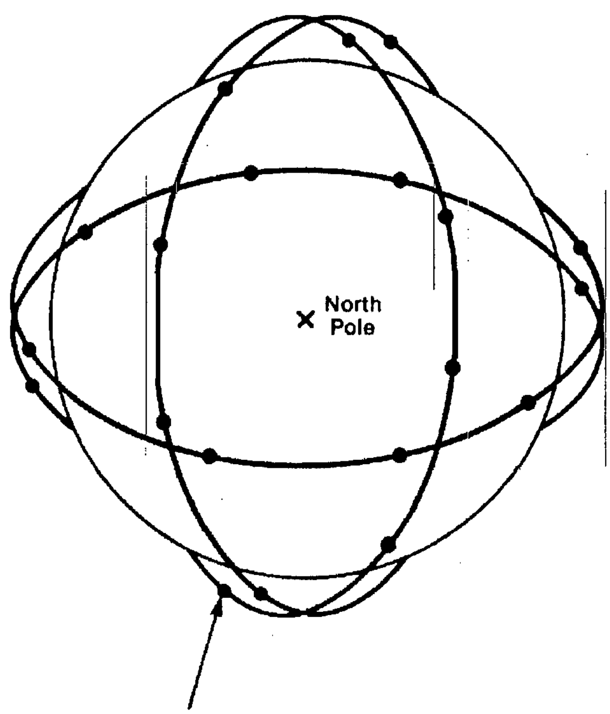


Figure 3.4 The number of satellites needed in a constellation to ensure that at least one satellite is over each Soviet ICBM field at all times depends on the effective range of the directed energy weapon. For every one defensive weapon required overhead a Soviet ICBM field to defend against a rapid Soviet attack, an entire constellation must be maintained on orbit. Since there are many Soviet ICBM fields distributed over much of the Soviet landmass, more than one satellite in each constellation would be in position to participate in a defensive engagement. The ratio of the number of satellites in the constellation to the number over or within range of Soviet ICBM fields is called the absentee ratio. If all Soviet ICBMs were deployed in one relatively small region of the U. S. S. R., the absentee ratio would be the same as the number of satellites in the constellation. Source: Author

Figure 3.5



O = Cluster of 5 chemical laser battle stations
Total of 32 X 5 = 100 battle stations

Figure 3.5 Constellation of hypothetical directed energy weapon satellites with 4,000 km range. The orbits are circular with 1000 km altitude. Each of the four orbital planes consists of eight positions spaced 45° apart around the circle. In the example given in the text, five chemical laser battle stations are clustered at each point shown in this figure, for a total of 32 x 5 = 160 battle stations. Source: Author

usually on the order of 10—offs'ts an oft-cited theoretical advantage of boost-phase intercept, namely, that intercepting one booster saves buying 10 interceptors for the booster's 10 RVS. On the other hand, coverage of the U.S.S.R.'s ICBM fields automatically gives good coverage of essentially all submarine deployment areas. Obviously the absentee ratio would be 32—the full constellation size—and not 32/3 = 10.7 if Soviet ICBM silos were not spread out so widely over Soviet territory but were deployed over a third or less of the Soviet landmass, so that only one of the 32 U.S. satellites was within range.

Three of the earlier described laser satellites in position over the Soviet ICBM fields are not enough to intercept 1,400 boosters if all or most of the boosters are launched simultaneously. Each satellite can only handle a few boosters because it must dwell for a time on each one. The time a chemical laser must devote to each booster depends on the satellite's position at the moment of attack—6.6 seconds for 4 Mm range, 1.7 seconds for 2 Mm range, etc. Taking 2 Mm as an average range for the 32-satellite constellation (hoping the Soviets do not choose a moment when most of the U.S. satellites are farther than 2 Mm from the ICBM flyout corridors to launch all their boosters simultaneously), a laser must devote an average of 1.7 seconds to each booster.

If the boosters in the future Soviet arsenal resemble the U.S. MX, and the defense waits 30 seconds or so to confirm warning and to wait for the boosters to climb to an altitude where the HF laser can reach, each booster is accessible for 150 seconds of its 180 second burn time. Each laser can therefore handle no more than 90 boosters, even with instant dewing of the beam from target to target. If 1,400 Soviet boosters were launched simultaneously, (1 ,400)/(90) ≅ 15 lasers would be needed in position, for a worldwide total (multiplying by the absentee ratio) of (10.7) X (15) = 160 satellites.

If the Soviets doubled their arsenal to 2,800 boosters, the United States would need to deploy another 160 satellites, possibly an uncomfortable cost trade for the United States.

What is worse, if the Soviets deployed 1,400 missiles in a single region of the U.S.S.R. (at a U.S.-estimated cost of $21 billion for Midgetman-like ICBMs; see section 2 above), the US would have to build, launch, and maintain on orbit an additional (32) X(1 400)/(90) ≅ 500 lasers plus their fuel and support equipment.

If Soviet boosters were covered with shielding material and spun during flight to achieve an effective hardness of, say, 60 kJ/cm², a laser would have to devote 10 seconds to each booster at 2 Mm range, requiring a sixfold increase in the number of satellites, to 960. Alternatively, the average range of each engagement could be reduced to keep the dwell time at 1.7 seconds, with corresponding increase in constellation density (fig. 3.4). Either way, the number of U.S. satellites would grow to nearly the number of Soviet boosters intercepted.

Table 3.1.—Variation of the Number of Chemical Laser Battle Stations Needed to Handle a Simultaneous Launch of Soviet ICBMs, Depending on Characteristics of the Soviet Arsenal and the U.S. Laser Defense

Departure from baseline	Number of Soviet boosters	Booster characteristics	Geographic distribution	Hardness (kJ/cm²)	Laser power (MW) and aperture diameter (m)	Approximate number of battle stations needed
Baseline	1,400	MX-like	Current Soviet	10	20/10	160
Booster number	2,800	MX-like	Current Soviet	10	20/10	320
Deployment geography	1,400	MX-like	One region	10	20/10	500
Booster hardness	1,400	MX-like	Current Soviet	60	20/10	960
Laser brightness	1,400	MX-like	Current Soviet	10	80/50 (100 times brighter)	20-30
Booster burn time	1,400	Fast-burn	Current Soviet	10	20/10	800-1,600
Booster burn time	1,400	SS-18-like	Current Soviet	10	20/10	90

SOURCE: Author.

If the United States developed a battle station 100 times brighter (using, say, a 80 MW laser with an effective mirror diameter of 50 meters), a few lasers overhead (20 to 30 total worldwide) could easily handle an attack of 1400 boosters hardened to 10 kJ/cm². If the boosters were hardened to 60 kj/cm², over 100 such lasers would be needed.

Deployment by the Soviets of 1400 fast-burn boosters would give the U.S. lasers just 20 to 40 seconds, rather than 200 seconds, to destroy all the boosters. The U.S. constellation would consequently need to grow by a factor 5 to 10, to 800 to 1600 satellites!

Table 3.1 summarizes how the size of the defensive deployment varies with the parameters assumed.

Requirements for a Chemical Laser Defense

Figure 3.6 displays the performance of various hypothetical HF lasers. Keeping the size of the battle station constellation down to a hundred rather than several hundred satellites means lethal ranges of at least 4 Mm with illumination times less than about 1 second, assuming the defense must be capable of intercepting 1,000 to 2,000 Soviet boosters with launches timed to keep the boosters as far from the U.S. lasers as possible. Further assuming Soviet booster hardening to at least 10 kJ/cm² results in a requirement for chemical lasers considerably brighter than the 20 MW, 10-meter laser described above. A hundredfold increase in brightness would be achieved by a laser with power 80 MW and effective mirror diameter 50 meters.

Such a laser would be about 10 million times brighter than the carbon dioxide laser on the Air Force's Airborne Laser Laboratory. The current Alpha laser program of the Defense Advanced Research Projects Agency (DARPA) aims at a construction of an HF laser of just a few megawatts and built only for ground operation. Nonetheless, there is no fundamental technical reason why extremely bright chemical lasers cannot be built. In theory, several lasers can be operated together so that the brightness of the resulting beam increases with the square of the number

Figure 3.6

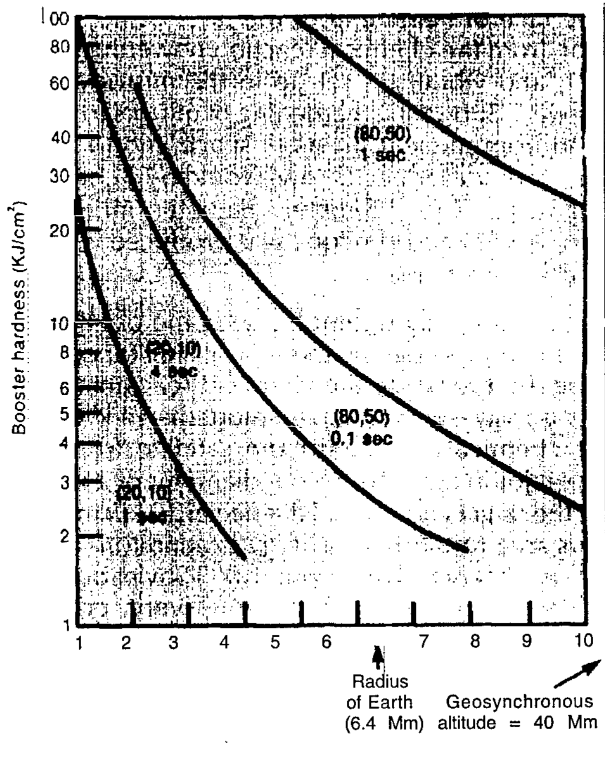


Figure 3.6 Lethal range versus booster hardness for HF chemical lasers of various sizes and dwell times. The labels on the curves have the format (laser power in megawatts, mirror diameter in meters) followed by the amount of time the laser devotes to destroying each booster. Source; Author

of lasers: 10 lasers combined in this way would produce a beam 100 times brighter than each individual laser. The trick is to arrange for the troughs and crests of the light waves from all the lasers to coincide. This theoretical prospect is unlikely to be realized with H F lasers, since their light is actually emitted at several wavelengths and with shifting patterns of crests and troughs.

To yield diffraction-limited divergence, the mirror surface must be machined to within a fraction of a wavelength of its ideal design shape over its entire surface. Since the mirror is over a million wavelengths across, avoiding small figure errors is a severe requirement. A number of small mirrors can obviously combine to produce one large optical surface if their positions are all aligned to within a fraction of a wavelength. The

mirrors must maintain perfect surface shape in the face of heating from the laser beam, vibration from the chemical reaction powering the laser, and vibrations set up in the mirror as it is slewed. Substantial hardening of mirrors to radiation from nuclear bursts in space and to the x-ray laser (described below) would be a challenging task. The 2.5-meter diameter mirror on NASA's Space Telescope was produced without these constraints.

An extremely optimistic outcome of HF laser technology—near the theoretical limit for converting the energy of the chemical reactants to laser energy—would require more than a kilogram of chemicals on board the satellite for every megajoule radiated. A spot diameter of 2 meters at the target and a lethal fluence of 10 kJ/cm^2 over this area results in an energy expenditure of 300 MJ per booster. Destroying 1,000 Soviet boosters therefore requires, reckoning very crudely, 300,000 kg of chemicals in position over the Soviet ICBM field, or perhaps 10 million kg on orbit worldwide. The space shuttle can carry a payload of about 15,000 kg to the orbits where the satellite battle stations would be deployed. About 670 shuttle loads would therefore be needed for chemicals, with perhaps another half as many for the spacecraft structures, the lasers and mirrors, construction and deployment equipment, and sensors. 1,000 shuttle missions for every 1,000 Soviet boosters (perhaps Midgetmen) deployed in reaction to the U.S. defense is an impractical competition for the United States. Use of H F chemical lasers for BMD therefore requires remarkably cheap heavy-lift space launch capability in the United States.

The remaining components of the chemical laser defense system—sensors, aiming and pointing technology, and communications— are for the most part generic to all directed energy weapons and are discussed in section 4. Section 5 presents countermeasures the Soviets might take to offset or nullify a chemical laser defense.

3.2 GROUND-BASED LASERS WITH SPACE-BASED MIRRORS

A slight variant of the previous concept puts the laser on the ground and mirrors in space, reflecting the light back down toward Earth to attack ascending boosters. This scheme avoids placing the laser and its power supply in space, though mirrors, aiming equipment, and sensors remain. The excimer and free-electron lasers considered for this scheme are in fact likely to be rather cumbersome, so ground basing them might be the only practical way to use them for BMD. The lasers would emit at visible or ultraviolet wavelengths about ten times shorter than the near-infrared wavelengths of the HF and DF chemical lasers in the space-based concept. Shorter wavelengths permit use of smaller (though more finely machined) mirrors. The high power available with ground basing suggests at least the possibility of impulse rather than thermal kill of boosters.

The term excimer is a contraction of "excited dimer." A dimer is a molecule consisting of two atoms. The dimers considered for these lasers contain an atom of noble gas and a halogen atom, making dimers like xenon fluoride (XeF), xenon chloride (XeCl), and krypton fluoride (KrF). The laser light comes from dimers in an excited upper state decaying to a lower state, just like in the HF laser. Excimer lasers tend to emit light in pulses rather than in a continuous wave. The population of upper-state molecules is provided by pumping with electric discharges in a rather complicated process. The population of lower-state molecules remains small because the lower-state dimer is unstable and quickly breaks up into its two constituent atoms. The pumping process for excimer lasers is inefficient, so only a small fraction of the energy put into the laser in the electric discharge emerges as laser light. Powerful excimer lasers would therefore be large and would need to vent large amounts of wasted energy; these characteristics make them unsuitable for space basing. Development of excimer lasers is at an early stage, and no excimer lasers exist with anything remotely approaching the characteristics needed for this boost phase intercept concept.

Figure 3.7

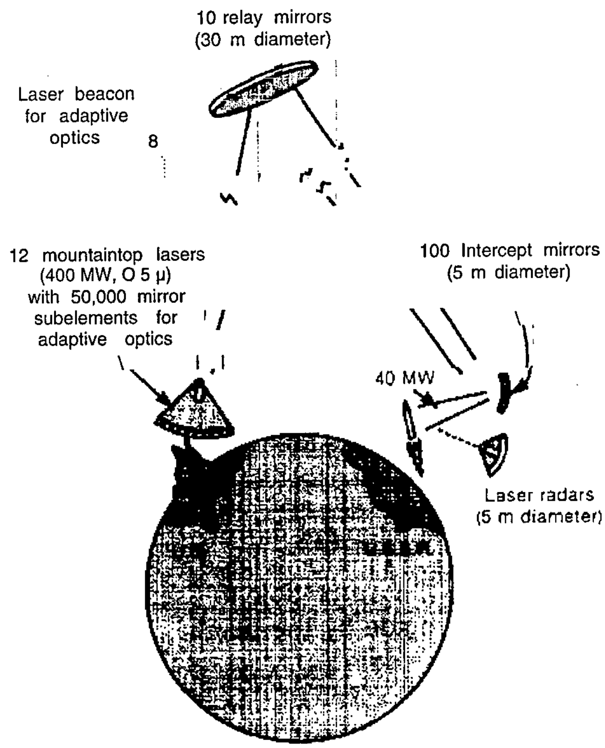


Figure 3.7 Illustrative configuration of ground-based excimer or free-electron laser and space-based mirrors for thermal kill of Soviet ICBM boosters. **Source: Author**

Power outputs achieved in the laboratory are still several orders of magnitude less than the average power needed for thermal kill, and the energy achieved in a single pulse is much smaller than the single-pulse energies needed for impulse kill.

The working of a free-electron laser (FEL) is more complicated.[4] As the name suggests, the light-emitter (lasant) is free electrons emitted from particle accelerator. Pumping therefore orignates in the electrical source powering the accelerator. The free electrons from the accelerator are directed into a tube called the wiggler that as magnets positioned along its length. The nagnets cause the electrons to wiggle back and orth as they transit the tube. As they wiggle, the electrons emit some of their energy as light. The presence of light from one electron causes others to emit in the usual cooperative manner of a laser, and a cascade begins. By adjusting the positions of the magnets and the energy of the electrons, the wavelength of the light can be tuned to any value desired. The only advantage of the FEL over excimer lasers is the high efficiency that can (theoretically) be obtained with the former. It has been suggested that it might even be possible to position FELs in space like HF chemical lasers. FEL operation at visible wavelengths is in its infancy, and the experimental devices used are many millions of times less powerful than those required in this BMD.

The BMD scheme calls for a large ground based excimer or free electron laser, relay mirrors at high altitude to carry the laser beam around the curve of the Earth, and intercept mirrors to focus the beams on individual boosters (fig. 3.7). The characteristics of a nominal system for thermal booster kill are easily ascertained. Suppose first that there are enough intercept mirrors so that the average range from mirror to booster is 4 Mm, and suppose the Soviet boosters are destroyed with 10 kJ/cm^2 deposited on a spot as small as several centimeters wide. Assume the excimer or free electron laser operates at about 0.5 microns, in the visible band. Then a 5 m intercept mirror will produce a spot 50 cm wide at 4 Mm range. If a half second of the main laser beam is devoted to each booster, then the required 10 kJ/cm^2 will be accumulated if the power reflected from each intercept mirror is 40 MW.

Only about a tenth of the power emitted by the ground based laser in the United States would be focused on the booster over the U.S.S.R. The remainder would be lost in transit through the atmosphere and in reflection from the two mirrors. Thus a 400 MW laser is required.

Passage through the atmosphere poses a number of problems for the primary laser beam. The most important source of interference is turbulence in the air, causing different parts of the laser beam to pass through different optical environments when exiting the atmosphere. Each part of the beam suffers a slightly different disruption, and the beam that emerges does not have the

[4] See Charles A. Brau, "Free Electron Laser: A Review, " *Laser ocus:* March 1981; *Physics Today,* December 1983, p. 17l

orderly arrangement of crests and troughs needed for diffraction-limited focusing from the intercept mirror. Without compensation for atmospheric turbulence, the ground-based laser scheme is completely impractical. Fortunately, the pattern of turbulence within the laser beam, though constantly changing, remains the same for periods of a few milliseconds. Since it takes only 0.1 millisecond for light to make a round trip through the atmosphere, the effect of turbulence on the laser beam can be compensated for with the following technique, called adaptive optics: A low-power laser beacon is positioned near the relay mirror. A sensor on the ground observes the distortion of the beacon beam as it passes through the atmosphere. The beam from the ground-based laser is then predistorted in just such a way that its passage through the same column of air transited by the beacon beam re-forms it into an undistorted beam.

Figure 3.7 shows the many components required by the ground-based laser concept. Since each Soviet booster requires 0.5 sec of beam at some time during its 200 sec. boost phase, four beams would be needed to handle **1,400** Soviet boosters launched simultaneously (assuming no retargeting delays), The lasers should be deployed on mountain tops to make atmospheric effects manageable, and enough should be deployed that at least four sites are always clear of cloud cover. The mirror on the ground would need to be tens of meters across and divided into tens of thousands of individually adjustable segments for predistortion of the wavefront. Each relay mirror would need to be accompanied by a beacon. Four large interception mirrors would be needed within 4 Mm of each Soviet ICBM flyout corridor, giving a worldwide constellation of a hundred or so.

The small laser wavelength means that all mirrors must be more finely machined than the mirrors for the chemical laser and can tolerate smaller vibrations and stresses due to heating from the laser beam. The small wavelength also results in a spot 10 times smaller at the target than the spot from a chemical laser beam at the same range. This small spot requires pointing accuracy ten times finer. Perhaps most important of all, the plume from the booster motor is too large to serve as target for such a narrow beam. Some way of seeing the actual missile body against the background of the plume is needed for the short-wavelength laser schemes (and for some configurations of chemical lasers). One answer to this problem, described in section 4 below, is to position near each intercept mirror a low-power laser and a telescope (a laser radar or ladar): the laser illuminates the booster and the telescope observes the reflected laser light, directing the pointing of the intercept mirror. The ladar telescope must have a mirror as large as the intercept mirror, since it must be able to "see" a spot as small as that made by the beam.

A single immense laser pulse that deposits 10 kJ/cm^2 in a very short time–millionths of a second rather than a second— might cause impulse kill rather than thermal kill, In impulse kill, the laser pulse vaporizes a small layer of the booster skin and surrounding air. The superheated gases then expand explosively, sending an impulsive shockwave into the booster. A strong enough shockwave might cause the booster skin to tear. The advantage of this kill mechanism is that it would be very difficult to protect boosters from it. The disadvantages are that impulse kill requires prodigious laser pulses and mirrors that can withstand them, and that the mechanism is poorly understood and depends on myriad factors like the altitude of the booster at the moment it is attacked.

3.3 NUCLEAR BOMB-PUMPED X-RAY LASERS: ORBITAL AND POP-UP SYSTEMS

The U.S. Government has revealed efforts at its weapon laboratories to use the energy of a nuclear weapon to power a directed beam of x-rays. Such devices are said to constitute a "third generation" of nuclear weapons, the first two generations being the atomic (fission) and hydrogen

(fusion) bombs. Each succeeding generation represented a thousandfold increase i n destructive energy, from a ton of high explosive to a kiloton fission weapon to a megaton fusion weapon. The third generation weapon uses the same amount of energy as the fusion weapon, but directs much of that energy toward the target rather than allowing it to escape in all directions. At the target, therefore, the energy received is much greater than the energy that would be received from a hydrogen bomb at the same range.

x rays lie just beyond ultraviolet light on the electromagnetic spectrum and have wavelengths about a thousand times smaller than visible light (see fig. 3.1). Compared to the infrared, visible, and ultraviolet lasers in the previous sections, the x-ray laser produces much more energy from its bomb pump, but the energy is spread out over a larger cone. The lethal ranges for boosters turn out to be roughly comparable for all these types of directed-energy device. Obviously the x-ray laser delivers all its energy in one pulse, so there is no question of dwell time on the target. Very short-wavelength x-rays penetrate some distance into matter (witness dental and medical x-rays), but the longer-wavelength x-rays produced by a laser device do not penetrate very far into matter or into the atmosphere.

orbiting and ground-based "pop-up" systems have been proposed as ways to make use of the x-ray laser for boost phase BMD. Both of these schemes have attractive features but also serious drawbacks. It could well be that the x-ray laser device, if a powerful one can eventually be built, will be more useful in other strategic roles than boost-phase BMD.

X-Ray Lasers

Little has been revealed about the characteristics of the bomb-pumped x-ray laser being studied by the United States (the so-called Excalibur device), but some general information can be deduced from the laws of physics and, to a lesser extent, from the scientific literature here and in the Soviet Unions

[5] F. V. Bunkin, V. 1. Derzhiev, and S. 1. Yakovlenko, *Soviet Journal of Quantum Electronics 11* (8), August 1981, p. 981. R. C. Elton, R. H. Dixon, and J. F. Seely, *Physics of Quantum Electronics 6* (1 978), p. 243. Michael A. Duguay, /&d., p. 557. G. Chapline and L. Wood, *Physics Today*, June 1975, p. 40.

Figure 3.8

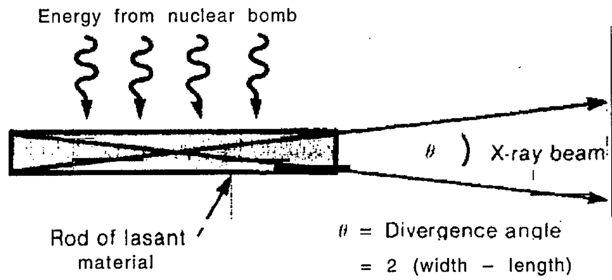


Figure 3.8 In an x-ray laser, a rod of lasant material is pumped to upper energy states by a nuclear bomb. Those cascades of downward transitions that travel lengthwise build up more energy than sideways-going cascades. As a result, most of the energy emerges from the ends of the rod into a cone with divergence angle equal to twice the rod width divided by its length. Source: Author

The pumping source for the x-ray laser is a nuclear bomb. The radiant heat of the born b raises electrons to upper energy levels in atoms of lasant material positioned near the detonation (the chemical nature of the lasant material has not been revealed). As the electrons fall back again to lower levels, it can happen that for a moment many atoms are in a given upper level and few in a lower level; this is the necessary condition for lasing from the upper level to the lower level. The wavelength of the emitted x-ray is determined by the energy levels involved. The wavelength of the laser under study in the United States is classified. We will use a round number of 1 nm.

Since x-rays are not back-reflected by any kind of mirror, there is no way to direct the x-rays into a beam with optics like the visible and infrared lasers. Nonetheless, some direction can be given to the laser energy by forming the lasant material into a long rod. Recall that a laser beam builds up when light from one lasant atom stimulates the upper-to-lower-level transition in another atom, which stimulates a third, and so on. The result is a cascade of light heading in same direction as the light from the original atom. The light pulse gets stronger and stronger as it traverses the lasant medium stimulating more and more transitions. In a long rod of lasant material, cascades that get started heading lengthwise down the rod are highly amplified by the time they leave the rod, whereas sideways-going cascades remain small. The result is that most of the laser energy

emerges as a beam aligned along the rod axis (fig. 3.8).

The projected capabilities of the x-ray lasers being studied in the U.S. are classified; but it is fairly easy to determine the upper limit to how powerful such a laser could possibly be. Whether R&D will succeed in making such a perfect laser cannot be said. But it will become clear that something very close to the perfect laser is required for boost phase intercept, though a less successful development would still yield a potent antisatellite weapon.

A l-megaton nuclear weapon releases about 4 billion megajoules of energy. By surrounding the bomb with lasant rods, most of this energy can be harnessed to pump the laser. Since the pumping mechanism for the x-ray laser is rather disorganized and wasteful, like the pumping mechanism for excimer lasers, at most a few percent of the bomb energy can be expected to end up in the laser beam.

The resulting 100 million megajoules or less of laser energy emerges from the rods into cones with relatively large divergence angle. It is easy to see why this divergence angle is much larger than the divergence angle obtained with the mirror-directed lasers treated in the previous section, The divergence angle is determined by the ratio of the width of the rod to its length, as in figure 3.8. A practical length for a rod is no more than about 5 meters. Making the rod thinner decreases the divergence angle, but beyond a certain point no further narrowing of the beam cone is possible. The limit arises from diffraction, just as with the infrared and visible lasers: the divergence angle of light emitted from an aperture (mirror, rod tip, or anywhere else) cannot be less than about 1.2 times the wavelength of the light divided by the diameter of the aperture. A very narrow rod therefore actually aggravates diffraction and produces a wide cone. Making the rod thinner results in no further narrowing of the beam when (1 .2) (wavelength) /(rod width) $\cong$ (2) (rod width)/(rod length). For an x-ray wavelength of 1 nm and a rod length of 5 meters, this equation yields an optimum rod width of 0.06 mm and a minimum achievable (diffraction-limited) divergence angle of 20 microradians.

A 1-megaton bomb-pumped x-ray laser can therefore deposit no more than about 100 million megajoules into a cone no narrower than about 20 microradians. The x-ray pulse from detonating such a perfect laser would deposit about 300 kJ/cm^2 over a spot 200 meters wide at 10 Mm range.

Interaction of X-rays with Matter

X-rays of 1 nm wavelength do not penetrate very far into matter: all the energy from such a laser would be absorbed in the first fraction of a millimeter of the aluminum skin of a missile. This paper-thin layer would explode, sending a shockwave through the missile. Thus the x-ray laser works by impluse kill.

Another consequence of the opacity of matter to x-rays is that the laser beam would not propagate very far into the atmosphere. The altitude to which the beam would penetrate depends on the precise wavelength, which is classified. For the nominal 1 nm wavelength described above, boosters below about 100 km would be quite safe from attack. If the wavelength were much shorter, the x-rays would penetrate lower, reaching perhaps 60 km altitude or so. In what follows, it will be assumed that boosters are safe from x-ray laser attack below about 80 km.

One last consequence of the physics of x-ray interaction with matter is noteworthy. When an atom of matter absorbs an x-ray, it emits an electron. As x-rays are absorbed, it becomes harder and harder to remove successive electrons. Finally further x-rays cannot remove further electrons, and the matter becomes transparent. This phenomenon, called bleaching, means that a strong x-ray laser beam can force its way through a column of air by bleaching the column, but a weak laser beam is completely absorbed. An x-ray laser in the atmosphere might therefore be able to attack an object in space because the beam is intense enough in the vicinity of the laser to bleach the air, whereas an x-ray laser in space could not attack objects within the atmosphere. This fact bodes ill for defensive space-based x-ray lasers attacked by similar lasers (or

even weaker ones) launched from the ground by the offense.

As with visible and infrared lasers, the lethality of an x-ray laser is subject to large uncertainties. The proper order of magnitude for the amount of x-ray energy per square centimeter that needs to be deposited on the side of a booster to damage it can be estimated fairly easily. But the actual hardness of a booster would depend on many design details in a way that is not fully understood at this time. A simple calculation indicates that 20 kj/cm^2 is a reasonable number to take for the hardness of a booster. This is about the same as for impulse kill by visible laser. An RV would be harder, and a satellite softer.

Orbital Defense Concept

The "perfect" x-ray laser whose characteristics were deduced above would be capable of intercepting a booster from geosynchronous orbit 40,000 km above the Earth. One laser would be needed for each Soviet booster. At lower altitudes, the rods surrounding the bomb could be gathered into several bundles and each bundle aimed at a different booster. At these lower altitudes, though, the absentee problem means that roughly one x-ray laser device would still need to be placed in orbit for each Soviet booster. Though the x-ray lasers are small and light compared to a chemical laser, the cost tradeoff involved in launching a new laser every time the Soviets deploy a new ICBM is obviously not a tolerable one for the United States.

The x-ray laser can attack the boosters after they have left the protective atmosphere but before burnout. Simultaneous launch of all Soviet boosters is not a problem for x-ray lasers in the way it is a problem for chemical lasers that must dwell on each target before passing on to the next. Fast-burn boosters are likewise not a crippling problem for an orbiting x-ray laser system *unless* they burn out before they leave the atmosphere, Other countermeasures, most notably the vulnerability of U.S. orbital x-ray lasers to Soviet x-ray lasers, are treated in section 5.

Pop-Up Defense Concept

The pop-up concept represents an attempt to avoid the one-laser-per-booster cost exchange and the vulnerability associated with basing the lasers in space (though crucial sensors remain space-based even in the pop-up scheme). The small size and light weight of the bomb-pumped lasers makes it possible to consider basing them on the ground and launching them into space upon warning of Soviet booster launch.

Figure 3.9 shows why basing the pop-up lasers in the United States is not practical. During the 200 seconds or so of burn time of a Soviet MX-

Figure 3.9

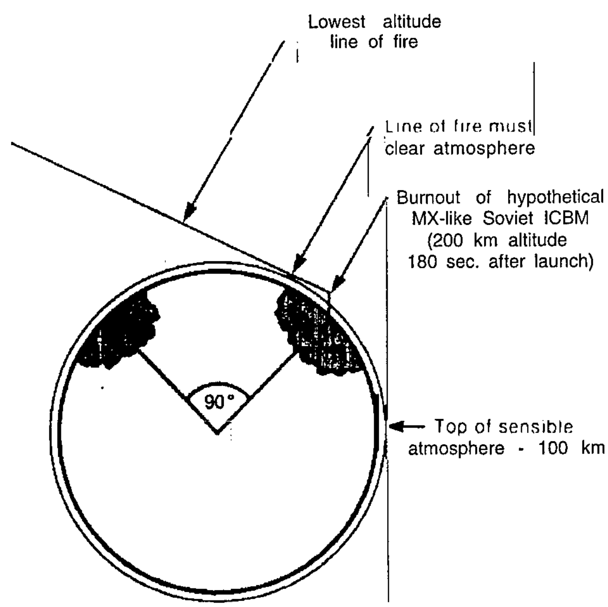


Figure 3.9 X-ray lasers launched from the United States on warning of Soviet ICBM launch would have to climb at least as high **as the line of fire shown in the figure within three minutes to intercept an MX-like Soviet ICBM. Such a huge fast-acceleration defensive booster would be many times larger than the Saturn V that took astronauts to the moon. Source: Author**

[6]A mallet or soft hammer blow applies an impulse per unit area of about 10 ktaps (0.5 kg hammer head, 5 m/sec striking velocity, 3 cm radius contact area; 1 tap = 1 dyne-sec/cm^2). To apply an impulse of this strength to the entire side of an ICBM booster requires a fluence F, whose order of magnitude can be estimated as follows: The cold mass absorption length (a) for 1 nm x-rays is about 0.5 milligrams/cm^2. If all the energy absorbed by the paper-thin absorbing layer were converted to kinetic energy, the boil-off velocity would be $(F/a)^{1/2}$, meaning an impulse per unit area of order $(Fa)^{1/2}$. 10 ktaps is therefore produced if F = 20 kJ/cm^2.

In reality, not all the deposited energy couples to the booster in this way. A more careful calculation of this lessened coupling has been performed by Hans Bethe (private communication).

like ICBM, the U.S.-based pop-up lasers would have to climb high enough to see the Soviet boosters over the Earth's horizon and have a line-of-fire unobstructed by the absorbing atmosphere. Climbing so high so fast requires a booster for the x-ray lasers that is many thousands of times larger than the Saturn V rocket that carried U.S. astronauts to the Moon.

If the British Government allowed the U.S. Government to base x-ray lasers in the United Kingdom, the lasers would be separated from Soviet ICBM silos by only 45 degrees of arc rather than 90 degrees as with U.S. basing. Even so, popping up to attack an MX-like Soviet booster would require an enormous fast-burn booster for the x-ray laser and would put it into position to attack the Soviet booster only seconds before burnout. If the Soviets depressed the trajectory or shortened the burn time of the offensive booster very slightly, or if the United States suffered any delay whatsoever in launching the defensive boosters after Soviet launch (instantaneous warning), this hypothetical U.K.-based system would be useless.

A final possibility would be launch of defensive lasers from submarines stationed immediately off Soviet coasts—in the Kara Sea or Sea of Okhotsk, separated from Soviet silos by about 30 degrees of arc–on SLBM-sized fast-burn boosters. With instantaneous warning, a sea-based laser might be able to climb to firing position a few seconds before burnout of a Soviet MX-like ICBM and would enjoy almost an entire minute of visibility to a slow-burning, high-burnout-altitude booster like the SS-18. Because of the short range, each bomb-pumped laser of the perfect design described above could attack many (over 100) boosters using many individual lasing rods. Such efficiency could well be essential, since a submarine cannot launch all its missiles simultaneously and might only be able to fire one defensive missile in the required few seconds. If the MX-like Soviet boosters were flown on slightly depressed trajections, if warning were not communicated to the submerged submarine promptly, if a human decision to launch defensive missiles were required, or if the Soviets deployed boosters that burned faster than MX, the sub-launched system would be nullified, Last, submarine patrol very near to Soviet shores suggests the possibility of attacking the submarine with shore-based nuclear missiles as soon as its position has been revealed by the first defensive launch. Other countermeasures are discussed in Section 5.

3.4 SPACE-BASED PARTICLE BEAMS

Beams of atomic particles would deposit their energy within the first few centimeters of the target rather than at the very surface as with lasers. The effects of irradiation with the particle beam could be rather complex and subtle and would probably depend on design details of the attacking Soviet booster. The result is uncertainty of several factors of ten in the effective hardness of an ICBM booster to beam weapon irradiation.

Only charged particles can be accelerated to form high-energy beams, but a charged beam would bend uncontrollably in the Earth's magnetic field. (There is one theoretical exception to this statement, described below.) For this reason neutral particle beams, consisting of atomic hydrogen (one electron bound to one proton) deuterium (one electron, one proton, one neutron), tritium (electron, proton, two neutrons) 01 other neutral atoms are considered. To produce a neutral hydrogen (H°) beam, negative hydro gen atoms (H –) with an extra electron are accel erated; the extra electron is removed as the bean emerges from the accelerator,

Two features of neutral particles beams domi nate their promise as boost phase intercept weap ons (leaving aside entirely the issue of counter measures). The first is the uncertain lethality o the beam. The second is the fact that the bear-r

cannot propagate stably through even the thinnest atmosphere and must wait for an attacking booster to reach very high altitude.

Generating Neutral Particle Beams

The accelerator that accelerates the negative hydrogen ion is characterized by its current in amperes, measuring the number of hydrogen ions per second emerging from the accelerator; and by the energy of each accelerated ion in electron volts (eV; 1 eV = 1 watt per ampere). Multiplying the current by the energy gives the power of the beam, so that a l-amp beam of 100 MeV particles carries 100 MW of power. Ground-based high-current accelerators and ground-based high-energy accelerators have been built and are operated daily in laboratories. One of the challenges for neutral particle beams as weapons is that they require both high current and high energy. Another challenge is to provide multi-megawatt power sources and accelerators in a size and weight suitable for space basing.

Magnets focus and steer the beam as it emerges from the accelerator. The last step is to neutralize the beam by passing it through a thin gas where the extra electron is stripped off in glancing collisions with the gas molecules, forming Ho from H-. The divergence angle of the beam is determined by three factors. First, the acceleration process can give the ions a slight transverse motion as well as propelling them forward. Second, the focusing magnets bend low-energy ions more than high-energy ions, so slight differences in energy among the accelerated ions lead to divergence (unless compensated by more complicated bending systems). Third, the glancing collisions that strip off the extra electron give the H atom a sideways motion. This last source of divergence is unavoidable and, by the Heisenberg uncertainty principle, cannot be controlled or compensated. It sets a lower limit on the divergence angle achievable with this method of producing neutral particle beams. Table 3.2 shows the divergence angle resulting from this third source, assuming perfect control of the first two sources. The divergence cone from a neutral particle beam is therefore about 10 times larger than the beam from the chemical laser of section 3.1 and 10 times smaller than from the x-ray laser of section 3.3.

A 100 MeV, 0.5 amp neutral tritium **(T°)** beam thus directs 50 MW of power into a cone of divergence angle 2 microradians, producing a spot 10 meters across at 5 Mm range. A target within this spot receives only 65 watts/cm², requiring 1.5 seconds of dwell time to deposit only 100 J/cm².

Booster Vulnerability to Particle Beams

As soon as the neutral particle beam hits the target, the remaining electron is stripped off, leaving the energetic proton (or deuteron or triton) penetrating deeply into the target. The proton scatters electrons in its path, giving up a small amount of its energy to the electron in each collision. When it has given up all its energy, it stops. For most of its path, it deposits energy uniformly. Thus if a 100 MeV **To** beam penetrates 4 cm into the propellant in a missile, it deposits about 25 MeV along each cm. Protons penetrate more deeply than tritons of the same energy, and all particles penetrate more deeply as they are given more energy (table 3.3).

Table 3.2.—Neutral Particle Beam Divergence Angle

	H"	T"
100 MeV	3.6 microradians	2.0
;00 MeV	1.4	1.0

Divergence angle introduced by stripping electrons from a beam of negative hlydrogen or tritium lons to produce a neutral beam This source of divergence ; an unavoidable consequence of the Heisenberg uncertainty principle applied o the sudden stripping of the electron If the satellite. based accelerator of the egative tons were absolutely perfect, this amount of divergence would remain

SOURCE Author

Table 3.3.—Penetration Range of Neutral Particle Beams Into Matter (in centimeters)

	H"		To	
	100 MeV	250 MeV	100 MeV	250 MeV
Solid propellant or high explosive (density 1.0 gm/cm³)	9.5	46.6	4.2	20.2
Aluminum	3.5	17.2	1.6	7.6
Lead	0.8	3.9	0.4	1.7

SOURCE Author

Figure 3.10

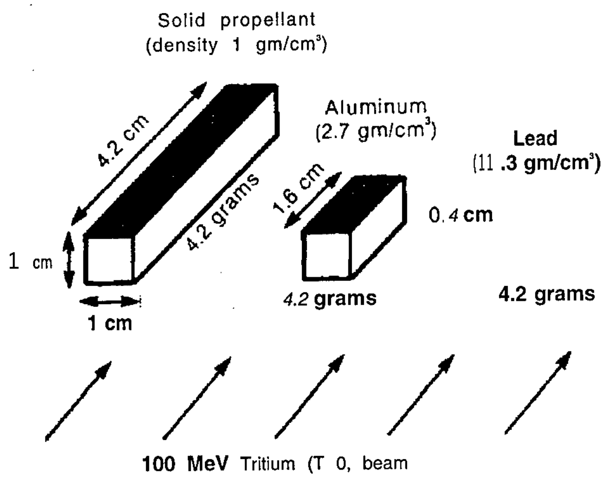


Figure 3.10 A neutral particle beam penetrates farther into an aluminum target than into a lead target but deposits the same energy per gram. Though the energy per gram needed to melt aluminum is well known, the utility of particle beam BMD concepts rests on the less certain destructive effects at lower levels of irradiation. Source: Author

Table 3.4.—Effects of Particle Beam Irradiation

Harmful effect	Energy deposition (Joules per gram)
Disruption of electronics	**0.01 –1 .0**
Destruction of electronics	10
Detonation of propellants, high explosive	200
Softening of uranium and plutonium	hundreds
Melting of aluminum.	1,000

Approximate energy deposition (radiation dose) required to produce various harmful effects in components of a missile booster and its payload Many other effects, such as melting of glue and plastic and rate-dependent effects, might also be Important

SOURCE Author

The target electrons that recoil from collisions with beam particles eventualy stop, and their energy appears as heat. The 100 MeV T° beam described above, depositing 100 J/cm² on an aluminum target, penetrates to a depth of 1.6 cm. The 1.6 cubic centimeter volume of aluminum **that absorbs this 100 joules** of energy weighs about 4 grams. The **effect** of the **beam is therefore to deposit about** 25 joules per gram throughout the first 1.6 cm of the target. The penetration depth is inversely proportional to the density of the absorbing material, so the same beam on a lead target would not penetrate as far but would **deposit the same energy** *per gram* **as it** did **in aluminum (fig.** 3.1 O).

The destructive effects of penetrating particle beams are therefore expressed in joules/gram deposited within the target rather than in joules/cm² on the surface of the target as with lasers. Table 3.4 shows the energy deposition needed to produce certain harmful effects. Melting the target is straightforward, but for the other effects at lower levels of irradiation the criteria are less clear. Heat effects in solid booster propellants and in the high explosive and special nuclear materials i n warheads depend on the design of the target. Effects on electronics, particularly transient disruption of computer circuits when electrons are scattered by a passing proton, are poorly known and doubtless quite complicated and specific to the target. Other components not shown in table 3.4 —plastics, glue, guidance sensors–make for a very complicated analysis. What is more, the particle beam might have to suffer the attenuation of passage through, say, two layers of aluminum and a layer of plastic before reach ing a sensitive component.

Uncertainties in the destructive or disruptive effects of small amounts of radiation from a par ticle beam weapon is the principal obstacle to stating what energy, current, and divergent angle would make this concept a candidate for boost-phase intercept.

Shielding to protect components from a neutra particle beam would necessarily be heavy but could still be an attractive countermeasure. It discussed in Section 5.

An Orbiting Neutral Particle Beam System

A critical limitation of neutral particle beam is that they cannot be aimed through even the thinnest atmosphere—air so thin that even the · ray laser beam could pass through easily. A neutral beam could not attack a Soviet booster un the booster reached at least 760 km altitude (ve sus about 80 km for the x-ray laser)[7]. Collision

[7]The stripping cross section on oxygen is about 1.5 megabarr Elastic scattering can also be important for beam loss, since the RM scattering angle can be larger than the beam divergence. The auth is Indebted to Dr. George Gull lespe of Physical Dynamics, In in La Jolla for resu lts of his Born approximation cross sectı calculations

between air molecules and H° strip the electron from the H°, and gradually all the remaining protons spiral off the beam axis into 200 km wide circles under the action of the earth's magnetic field.

An MX-like Soviet booster could be attacked between 160 km altitude and burnout at 200 km, a period of about 10 seconds. This short attack window means that the neutral beam cannot afford to dwell for long on each booster.

It is impossible to state with confidence the resilience of an ICBM booster to irradiation with a neutral particle beam. But it is likely that faith would have to be placed in degradation of electronics and other subtle effects, rather than in gross structural damage, for the beam weapon to stand a chance as an economical defense system (ignoring the issue of countermeasures entirely).

Consider again a battle station producing a 0.5 ampere beam of 100 MeV tritium (T°) atoms with 2 microradian divergence. This beam carries 400 watts/cm^2 at 2 megameters range. To do structural damage to the outer few centimeters of a missile's body might take some 2 kJ/cm^2 (depositing 500 J/gin in 1.6 cm depth of aluminum, for instance), requiring 5 seconds of dwell time at this range. Since the available dwell time is only about 10 seconds, each beam could handle only two boosters. With a constellation size of almost 100 for 2 Mm range (fig. 3.4), this kill criterion results in a preposterous system where the U.S. deploys 50 space-based accelerators for every one Soviet booster deployed in one region of the U.S.S.R.

If the assumed Soviet booster hardness is reduced by 100 times, corresponding perhaps to transient upset of unshielded electronics, each satellite can destroy 200 boosters at 2 Mm range, meaning an overall tradeoff of one U.S. accelerator deployed for each two Soviet boosters deployed. Alternatively, the constellation can be thinned out to an effective range of 5 Mm, where each satellite at this range can destroy only 32 boosters but the constellation size is only about 16—still a one-to-two trade of battle stations for Soviet boosters. Such a system scarcely seems promising in terms of cost exchange.

obviously the neutral particle beam would stand no chance of intercepting a fast-burn booster that burns out well within the protective atmosphere. Even an MX-like booster that flew a slightly depressed trajectory would be invulnerable.

A Theoretical Electron Beam System

Physical theory[8] holds out the prospect of one other type of beam besides the neutral particle beam. Under certain circumstances, an electron beam might be able to propagate through the extremely thin air of near-earth space without bending. In this scheme, a laser beam would first remove electrons from air molecules in a thin channel stretching from the battle station to the target, leaving a tube of free electrons and positive ions. The high-energy, high-current electron beam would then be injected into the channel. The beam electrons would quickly repel the free electrons from the channel, leaving the beam propagating down a positively charged tube. The attractive positive charge would prevent the electrons from bending off the beam path under the influence of the geomagnetic field and would also prevent the mutual repulsion of electrons within the beam from causing the beam to diverge. The result would be straight-line propagation to the target, where their effect would be similar in most respects to the neutral particle beam. This scheme will not work for a proton beam.

The physics of intense beam propagation through thin gases is so complex that experiments will be needed to determine whether this concept is even feasible in principle. If so, the concept would resemble the neutral particle beam, with the added requirement for the channel-boring laser and perhaps the ability to intercept boosters at slightly lower altitudes than the neutral counterpart.

8R. B. Miller, *The Physics of Intense Charged Particle Beams* (New York, 1982, ch. 5.

3.5 SPACE-BASED KINETIC ENERGY WEAPONS

Kinetic energy is the name given to the energy of a moving projectile. Use of this term makes ordinary weapons using aimed projectiles into "directed kinetic energy" weapons.

The phenomenology of high-velocity collisions between a projectile and a structure like a booster is surprisingly complex, but in general lethality is not an issue for kinetic energy boost phase intercept concepts. Rather, the problem is getting the projectile from its satellite base to the ascending booster in time to make an intercept. Schemes where the projectile is carried by a small rocket launched from the satellite suffer most directly (leaving aside countermeasures) from a combination of the large number and large size of the rockets needed for adequate coverage. In particular, the most conspicuous public example of the kinetic energy approach, the High Frontier Project's Global Ballistic Missile Defense (GBMD) concept,[9] has extremely limited capability for boost phase intercept of current Soviet ICBMs and would have no capability at all against a future generation of MX-like boosters.

Kinetic Energy Concepts

Rocket attack of ICBM boosters is obviously not as novel as beam attack, but it entails rather more complexity than appears at first blush. The rocket needs radio or other guidance by long-range sensors on its carrier satellite (or other satellites) to direct it to the vicinity of its target, since it is impractical to put a long-range sensor on each rocket. Once in the vicinity of the target booster, the interceptor needs some form of terminal homing sensor and rather sizeable divert rocket motors. Homing on the plume of the ICBM booster is not straightforward, since attacking the plume will obviously not harm the booster: the booster body must be located in relation to the plume. These complications introduce opportunities for offensive countermeasures.

An alternative to rocket propulsion would be to expel the homing vehicles at high velocity from a gun. So-called rail guns use a clever scheme to convert electrical energy to projectile kinetic energy. Since a 10 kilogram projectile ejected with 5 km/see velocity carries 125 megajoules of energy (the amount of energy expended by a 25 megawatt chemical laser in 5 seconds of dwell on a booster), the power requirements of the gun schemes are imposing. Providing chemical fuel or explosives to power a gun therefore involves the same magnitude of on-orbit weight as the chemical laser.

Doing away with the homing sensor and replacing the guided projectile with many small fragments is not an attractive alternative, since the needed fragments end up weighing far **more than the guided projectile.**

The Importance of Projectile Velocity

In the 300 or so seconds from launch to burnout of a slow-burning booster like the SS-18, the defensive rocket or other projectile must fly from its satellite to the path of the booster. Such a booster burns out at about 400 km altitude, so if the projectile wishes to use the entire 300 seconds of boost phase to travel to its quarry, it must make its intercept at 400 km altitude.

Suppose now that the projectile's rocket or gun launcher can give it a maximum velocity of 5 km/see with respect to the carrier satellite. In the 300 seconds of available travel time to its target, the projectile cannot fly more than (5 km/see) **x** (300 see) = 1.5 Mm from its carrier. Each carrier therefore has an effective range of 1.5 Mm (fig. 3.1 la).

Referring to figure 3.4, a constellation of about 240 carrier satellites are needed for continuous coverage of the Soviet Union. Since Soviet ICBMs are spread over much of the country, 10 or so of the carrier satellites might be able to participate in a defensive engagement. The absentee ratio is therefore about 24, The 10 satellites over the U.S.S.R. **at** the moment of a massive Soviet attack need to be able to handle all 1,400 boosters, meaning each satellite needs to carry 140 projectiles.

An idealized rocket accelerating a 15 kg guided projectile to 5 km/see velocity would need to weigh about 80 kg (a real rocket with this capa-

[9] General Daniel O. Graham, *The Non-Nuclear Defense of Cities: The High Frontier Space-Based Defense Against ICBM Attack* (Cambridge: Abt Books, 1983).

Figure 3.1 l(a)

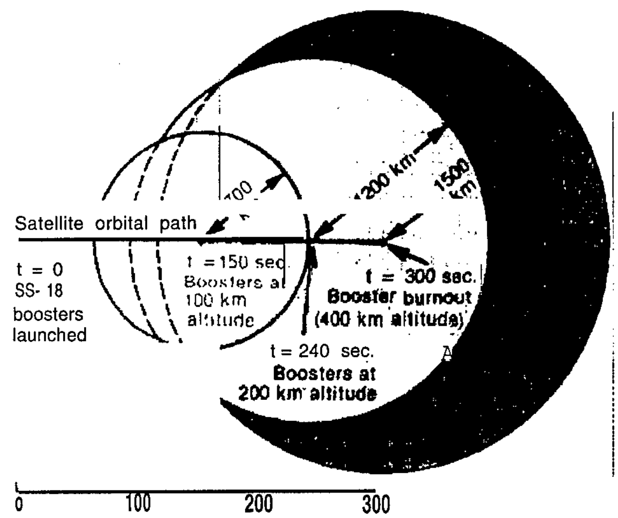
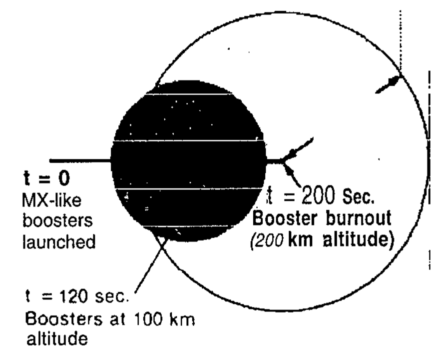


Figure 3.1 l(b)



(b) Same as (a), except the target is the faster-burning MX.

Figure 3.11 View from above (looking down on earth) of coverage by a satellite carrying kinetic energy boost-phase intercept vehicles. The satellite is deployed **in a *400* km orbit. At time t =0, offensive boosters are launched. The satellite can make intercepts by shooting downward or wait until the boosters rise to their burnout altitude and fire nearer to the horizontal. The longer after launch the intercept is made, the farther the rocket intercept vehicles can travel from the satellite to make the intercept. Smaller circles thus correspond to downward firing, larger circles to horizontal firing. The satellite moves from left to right in accordance with its 8 km/see orbital velocity. The area enclosed by all the circles taken together gives the total coverage of the satellite and determines how many satellites are needed in the worldwide constellation for continuous coverage of opposing ICBM fields. All dimensions are to same scale.**

(a) The satellite-based kinetic energy interceptors are capable of 5 km/see velocity relative to the satellite. The attack is on a slow-burning Soviet SS-18.

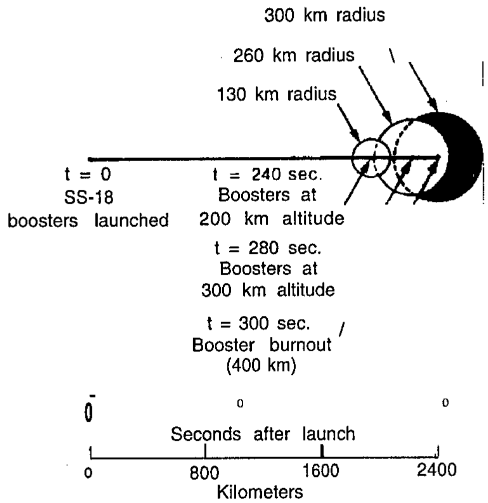
bility would weigh more like 200 kg). Each carrier satellite must therefore weigh (1 40) x (80) = 11,000 kg. Less than twice this weight can be carried by the space shuttle into the appropriate orbits, so establishing the total 240 satellite constellation requires over 120 shuttle launches in this highly idealized model with idealized rockets and weightless carrier satellites. (A more careful estimation of interceptor design would more than double this load.)

From this baseline; we can consider five excursions:

1. Suppose the velocity capability of the interceptor is doubled to"1 0 km/sec, doubling the effective flyout range to 3 Mm. At this range, 48 satellites complete the constellation, with perhaps as many as eight of them in position to participate in the engagement. Each of the eight satellites must handle 175 Soviet boosters.

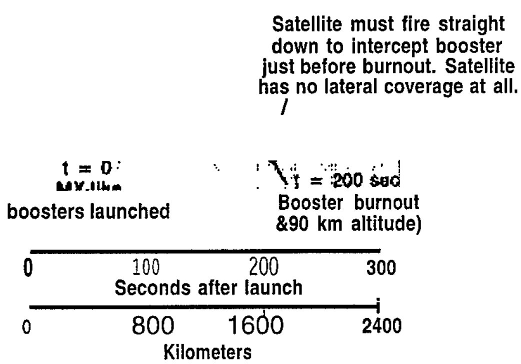
   Doubling the velocity capability more than doubles the weight of the rocket required. The reason is simple: to increase the velocity requires more propellant, and the extra propellant must itself be accelerated, requiring yet more propellant. The rocket weight thus grows exponentially with velocity capability. The idealized 10 km/sec rocket weighs ***420*** kg. Each satellite carrying 175 rockets then weighs 75,000 kg and requires some five shuttle launches to orbit. The result is that over 200 shuttle launches are required to orbit the entire (idealized) defense system. Increasing the velocity capability is therefore no escape from large on-orbit weights.
2. The current Soviet ICBM force consists largely of slow-burning liquid-fueled boosters distributed widely over the Soviet Union. Consider the consequences for the U.S. kinetic energy defense system if the Soviets de-

Figure 3.1 l(c)



(c) The High Frontier Global Ballistic Missile Defense (GBMD) concept, with intercept vehicles capable of only 1 km/see velocity relative to the satellite. Intercept of SS-18. In the actual High Frontier proposal, the satellites are in 600 km orbits, giving them even less coverage than shown here.

Figure 3.11(d)



(d) The High Frontier concept has no capability whatsoever for boost-phase intercept of MX.

ploy 100 faster-burning MX-like boosters in one region of the country, so that defensive interceptors have less time to fly to their targets and only one satellite overhead participates in the engagement. MX burns out 200 seconds after launch, so each satellite has an effective range of 1 Mm, requiring a constellation of 400 satellites (fig. 3.11 b).

Each satellite must carry the 100 80-kg rockets needed to handle the attack. An exchange ratio of four 8,000 kg U.S. defensive satellites for every Soviet offensive booster deployed is surely an economic advantage for the U.S.S.R.

3. Soviet deployment of 1,000 Midgetman-like boosters would require a compensating deployment of 400 U.S. satellites, each weighing at least 80,000 kg. A system that forces the United States to such a response is clearly absurd.
4. Soviet fast-burn boosters would be totally immune to the kinetic energy defense system. An interceptor on a satellite in 400 km orbit (lower orbits shorten satellite lifetimes because of atmospheric drag) could not even descend straight down to the fast-burn booster's 100 km burnout altitude in the required 50 seconds, much less have any lateral radius of action.
5. Intercepting SS-18 or MX post-boost vehicles is clearly easier, from the point of view of flyout velocities, than boost-phase intercept. Satellites at 700 km or so altitude would have 500 seconds to fly out to meet the bus when it ascended to their altitude, giving a 2.5 Mm lethal radius.

In conclusion, a rocket-propelled kinetic energy system acting against today's Soviet ICBM arsenal (with no Soviet countermeasures) would require many heavy satellites and would be a dubious investment for the U.S. Soviet deployment of MX-like or Midgetman-like boosters would nullify the United States defense or force the U.S. to large investments in new satellites.

Analysis of the High Frontier Concept

The High Frontier Program[10] proposes a Global Ballistic Missile Defense (GBMD) using rocket propelled interceptors for boost phase intercept. This concept claims to have some utility, at least against the present Soviet ICBM arsenal.

The concept consists of 432 satellites (24 planes of 18 satellites in circular orbits inclined 65 degrees) at an altitude of 600 km. A velocity

[10]Ibid

capability of I km/see relative to the satellite ("truck") is attributed to the interceptor. The interceptors are apparently command guided to the vicinity of the target. The homing sensor is not specified, but short wave infrared homing on the hot rocket plume is implied.

Consider this concept defending against the SS-18 in its boost phase. Since the SS-18 burns out at 400 km altitude 300 seconds after launch, each GBMD satellite has a 0.3 Mm radius of action. Since the satellites are deployed at 600 km altitude, the interceptor must descend 200 km to make an intercept just before burnout, resulting in a lateral radius of action of 0.22 Mm (compare fig. 3.11c, where the satellites are assumed deployed at ***400*** km altitude). With a range this small, thousands of satellites would be needed worldwide for continuous coverage of Soviet ICBM fields. The High Frontier concept with only 432 satellites would therefore have meager coverage of Soviet ICBM fields.

The GBMD concept would have no capability whatsoever against an MX-like booster. Such a booster would burn out before the interceptor could reach it, even if the interceptor were fired straight down (fig. 3.11 d).

It is possible that the High Frontier concept is designed for post-boost intercept rather than boost phase intercept. Its coverage for post-boost intercept, though greater than for boost-phase intercept, would still be only partial. The only example given in the description' of the system is of ***boost phase*** intercept of an SS-18, however. In this example the interceptor is launched 53 seconds ***before*** launch of its target booster, though no explanation is given of how the U.S. defense knows in ***advance*** the precise moment at which the Soviets would launch a given booster. This early launch allows the interceptor to reach its target seconds before burnout. Plume homing, a technique inappropriate for bus intercept, is also implied for the High Frontier concept. Post-boost intercept permits some RVs to be deployed on trajectories carrying them to the United States before intercept; and the entire bus, with its warheads, would continue on to the U.S. after the interceptor collision, with uncertain consequences.

It would therefore appear that the technical characteristics of the High Frontier scheme result in a defensive system of extremely limited capability for boost phase intercept of present Soviet ICBMs and no capability against future MX-like Soviet boosters, even with no Soviet effort to overcome the defense.

' ' I bid., p. 103.

3.6 MICROWAVE GENERATORS

Microwaves are short-wavelength radio waves used in radar, satellite communications, and terrestrial communications relays. A number of ideas have been conceived for generating microwaves in space and directing them towards ascending ICBM boosters. The principal technical problem with this type of BMD, generator technology aside, is the uncertain effect the microwaves would have on their target.

The microwaves would propagate through the atmosphere unattenuated at all but the highest power levels. The weapon divergence angle would be very large, producing a spot many km wide at a few hundred km range. From these considerations the following concept emerges: As Soviet ICBMs lift off from their silos, a few microwave generators in space bathe the silo fields with microwaves.

At high power levels, as in a microwave oven, microwaves cause heating in many materials. But in the BMD scheme, the divergence cone is so large that even a prodigious amount of energy emitted from the generator would lead to very small energy deposition per square centimeter on the target (millions of times less than lasers). The microwave pulse received at the booster

would resemble the high frequency component of the electromagnetic pulse (EMP) from a high-altitude nuclear detonation. However, even weak microwaves can upset sensitive circuitry if they can reach it.

A metal skin on the booster **would stop the microwave pulse altogether from reaching internal electronics.** The microwave defense must therefore hope that some aperture or conduit is available into the booster, whether by design (as in an antenna), inadvertence, or poor maintenance. If so, and if the electronic circuitry is not or cannot be made resistant to disruption or burn-out, the part of the booster's performance dependent on those electronics (perhaps accurate guidance) would be affected.

Because of the very uncertain lethality of microwaves, deployment of space-based generators (if they can ever be built) would be a harassing tactic rather than a confident-kill ballistic missile defense.

3.7 OTHER CONCEPTS

Other directed energy concepts suitable in theory for ballistic missile defense have been broached from time to time. Some of them are listed below. **It is** quite possible that in a few years time a revisit to this subject will find a new panoply of concepts enjoying the front rank of discussion.

1. **Short-wavelength chemical lasers would combine the simplicity and efficiency of the** HF chemical laser with the small mirrors of the short-wavelength excimer and free-electron lasers. Though some ideas have been advanced along these lines, no laser exists which can be said to be a candidate to fulfill this theoretical promise.
2. **Explosive-pumped lasers and particle beams** are said to be under study in the Soviet Union.[12] Such devices might possibly be quite compact, each bomb generating a single huge pulse for impulse kill of a booster. All these schemes are at a very early conceptual stage.
3. **Antimatter beams would penetrate into a** target just like ordinary particle beams, except that when the antiparticle reached the end of its range it would annihilate a particle in the target, freeing a large extra amount of harmful energy. Acceleration of antimatter beams is accomplished exactly as with particle beams, and laboratory beams of antimatter have been used routinely in pure research. One important difference is that antimatter is not freely available in the universe as is matter; the antimatter for the accelerator would have to be produced by the defense system, a formidable and complex undertaking. It is not clear that the extra energy released in the target by an antimatter beam would justify the trouble of producing the beam.

[12] *Aviation Week and Space Technology,* July 28, 1980, p. 47.

Section 4

OTHER ESSENTIAL ELEMENTS OF A BOOST-PHASE INTERCEPT SYSTEM

Section 4

OTHER ESSENTIAL ELEMENTS OF A BOOST-PHASE INTERCEPT SYSTEM

The previous section treated only the defensive weapon itself, the so-called "kill mechanism. But if beam weapons ever evolve to the point where deployment is a serious possibility, other elements of the overall defensive system will emerge as equally important determinants of cost and level of protection. After all, the interceptor missile in traditional BMDs has not been the central focus of attention or technical debate since the 1950's, when it became clear that a "bullet could hit a bullet. " Discussion of BMD at that point passed to the difficult issues of radar performance, data processing capability, and vulnerable basing of defensive components—issues that had nothing to do with the kill mechanism. In a similar manner, the other essential elements of a boost-phase intercept system will figure more prominently in discussion of boost-phase BMD if and when the kill mechanisms—lasers, mirrors, accelerators—are in hand. These other essential elements introduce their own technological problems and opportunities for offensive countermeasures. If traditional BMDs are any guide, provision of a kill mechanism will be just the beginning of making an efficient, robust defensive system.

4.1 TARGET SENSING

Locating and tracking an ICBM booster with enough precision to aim a directed-energy weapon is not as straightforward as is sometimes supposed. it is true that booster motors emit hundreds of kilowatts of power at short- and medium-wave infrared (SWIR and MWIR) wavelengths of a few microns. Sensors can detect these plumes at great distances from the earth. Plume sensing is used today for early warning of missile attack to support launch of bombers and airborne command posts and launch under attack of ICBMS.

To be useful for directed-energy BMD, however, the sensor must localize the booster within an area as small as the beam spot. Otherwise the beam would have to sweep wastefully back and forth over the area of uncertainty. Small divergence beams must therefore be accompanied by sensors with small angular resolution.

Diffraction limits the angular resolution of a sensor in the same way it limits the divergence angle of a laser. A large infrared telescope with 5 m diameter mirror observing MWIR booster emission at 4 micron wavelength would have angular resolution no more precise than a micro radian. Such a sensor affixed to each battle station in a defensive constellation would localize ascending boosters to within a spot 5 m wide at 5 Mm range. At this range, the (illustrative) systems described in Section 3 have spot sizes: 1.5 m for the H F laser, 0.6 m for the ground based laser, 10 m for the neutral particle beam, and 100 m for the x-ray laser. Even a large infrared sensor on each battle station would therefore be inadequate for directing the laser beams at a point source of MWIR light, marginal for directing the neutral particle beam, and adequate for directing the x-ray laser. The actual situation would be worse still, since the booster is not a point source. The booster plume would be larger than the laser or particle beam spots, and the booster body would need to be located in relation to the plume to avoid wasting beam time attacking the plume.

For directed-energy weapons with small divergence angles, therefore, sensing the conspicuous rocket plume is inadequate. Another kind of sensor must be introduced into the BMD system. For finer angular resolution one looks to shorter wavelengths, in the visible or ultraviolet. At these wavelengths the sensor must provide its own illumination. A so-called laser radar or ladar is the only practical solution. In a ladar, a low-power

Section 4

OTHER ESSENTIAL ELEMENTS OF A BOOST-PHASE INTERCEPT SYSTEM

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visible or ultraviolet laser shines on the booster body, and a telescope on board the battle station senses the reflected light.

Besides the annoyance of a new laser and new sensor, the necessary introduction of ladar into the boost-phase system creates opportunities for the defense to spoof and blind the offensive sensor.

Kinetic energy systems do not need precision long-range sensing, since the rocket or guided projectile homes on the target when it comes within short range. The terminal homing might involve deducing the location of the booster body in relation to its MWIR plume, homing on low-power laser light shined from a defensive satellite and reflected from the target, or some other method. These homing methods are susceptible to countermeasures.

Though this Background Paper treats only intercept of the booster proper, it is worthwhile pausing to consider tracking of the post boost vehicle or bus. The low thrust levels of the post boost vehicles's rocket motors, their intermittent operation, the possibility of dimming them with propellant additives, and the possibility of building decoys with small rocket motors all suggest that MWIR plume sensing is not practical for post boost intercept. The alternatives are ladar or radar, suggesting again many opportunities for countermeasures.

4.2 AIMING AND POINTING

The directed-energy beam must be aimed and stabilized as accurately as it is collimated. If the beam waves around too much, the effective divergence increases, and the beam wastes energy missing the target. The mirrors or other mechanism steering the beam must be stabilized despite vibrations in the battle station caused by the beam's large power source.

In the 15 milliseconds the beam takes to travel from the battle station to a booster 5 Mm away, the booster moves about 50 m. A narrow beam must therefore lead the target. In one second of dwell time, the target moves several km; the beam must remain on the target, sweeping through the sky at the necessary angular rate while still maintaining its aim and jitter control.

4.3 INTERCEPT CONFIRMATION

A desirable, though perhaps not essential, function of BMD systems is confirmation that an attempted intercept succeeded. This function is sometimes called "kill assessment. " Intercept confirmation would allow the beam to move onto subsequent boosters with more than a statistical estimate that its previous task was accomplished. Structural damage to the booster would presumably be revealed by an erratic course or burn pattern, though it might be difficult to say in advance exactly what the sensor's view of the wounded booster would be. Subtle damage inflicted by a particle beam or microwave generator might not be visible. Damage to a bus would be difficult to assess and interpret if the debris, including RVs (perhaps arranged by the offense to separate from the bus under extreme circumstances), continue on their ballistic course to the continental United States.

Related to intercept confirmation, and ultimately more serious, is the question of determining whether the beam is missing the target (perhaps by slight misalignment of sensor and beam boresights, miscalibration of aiming mechanisms, etc.) and, if so, by how much and in what direction. It might be possible to observe a glowing column of air where a laser beam passes through the at-

mosphere. Some clever but elaborate schemes have been devised to track a neutral particle beam. Obviously each new complication added to the defensive system potentially creates new opportunities for offensive countermeasures.

4.4 COMMAND AND CONTROL

The crucial infrastructure of command and control of a complex system is always the last to take shape, since it integrates the workings of all the separate components. It is easy to ignore the difficulty of accomplishing this last step at this early stage when the other components of a boost phase system are not yet remotely in hand. The command and control system of a boost-phase intercept system would comprise communications links among its far-flung components, data processing to support sensors and battle station operations, and "battle management" software incorporating all the instructions and decisions needed to run the defensive engagement and to coordinate the defense with U.S. offensive forces.

Communications and data processing are two areas of technology where there is the least pessimism—looking two or so decades into the future when boost-phase systems could presumably be deployed–that technology will be able to meet the needs of directed-energy defenses. Compact, lightweight, and rapid data processing hardware is virtually assured, though interesting questions attend on hardening, reliability, and lifetime in space. Software would be expensive and would introduce issues of reliability and security from programmer sabotage. Satellite-to-satellite communication via extremely high frequency radio and laser offers high data rates and virtual immunity to jamming from earth or from space.

Command and control for BMD does introduce two interesting issues to which technology cannot provide an answer. The first is the impossibility of testing the whole defense system from end to end in a realistic wartime setting. Unlike the air defense systems of World War 11, which learned through attack after attack to exact kill rates of several percent, the BMD system would have to work near perfectly the very first time it was used. The second issue is the likely need for the defense to activate itself autonomously, since there would be no more than a minute for human decision,

4.5 SELF-DEFENSE

Consideration of anti-satellite (ASAT) attack (see Section 5.1), and analogy with traditional BMD systems (where vulnerability of key radars, data processors, and other components is usually the chief limitation on defense performance) suggest that self-defense mechanisms could well end up being a large part of the defense system. These mechanisms could include shields, escort weapons, and countermeasures to ASAT sensors. Unless and until a credible overall approach to satellite survivability is found, one cannot specify the needed hardware.

Ground-based BMD lasers and pop-up x-ray lasers would obviously need to be protected from precursor attack by cruise missiles and other delivery systems. '

4.6 POWER SOURCES

Chemical lasers, x-ray lasers, and rocket-propelled kinetic-energy interceptors have power sources integral to the weapon, but excimer lasers, free electron lasers, neutral particle beams, and rail guns would need sources of electrical power and the equally important means to convert electricity into a form usable by the weapon ("power conditioning"). Space basing obviously complicates the task. Large commercial power plants on the ground produce about 1,000 MW of power, and directed energy weapons might require hundreds of MW. On the other hand, the power plants on defensive satellites need not work reliably for many years but only once for a short time, and they need not be very highly efficient. The three alternatives for space power are fuel burning, explosives, and nuclear power. Starting up a large power source in seconds from a condition of dormancy poses some interesting design issues.

Section 5

COUNTERMEASURES TO BOOST-PHASE INTERCEPT

Section 5

COUNTERMEASURES TO BOOST-PHASE INTERCEPT

Countermeasures that limit the effectiveness of traditional ballistic missile defenses—decoys, radar blackout, defense suppression, etc.—are well known. A comparable set of countermeasures, no less daunting for being less familiar, faces the designer of boost-phase defenses.

The need to resort to countermeasures imposes a cost on the offense. This cost is measured in money to build more or specialized offensive hardware, but also in the time needed to do so, in constraints upon the type of attack the offense can incorporate in its nuclear planning, and in the confidence with which it can predict a "successful" outcome of the strike.

Every BMD system actually proposed for deployment would be accompanied, at least ideally, by, first, an analysis of its degradation in the face of an improving Soviet offense and, second, by an analysis of how much it would cost for the United States to improve its defense in such a way as to avoid being overcome.[1]

[1]See *Ballistic Missile Defense*, ed. Ashton B. Carter and David N. Schwartz (The Brookings Institution, 1984), ch. 4.

Figure 5.1

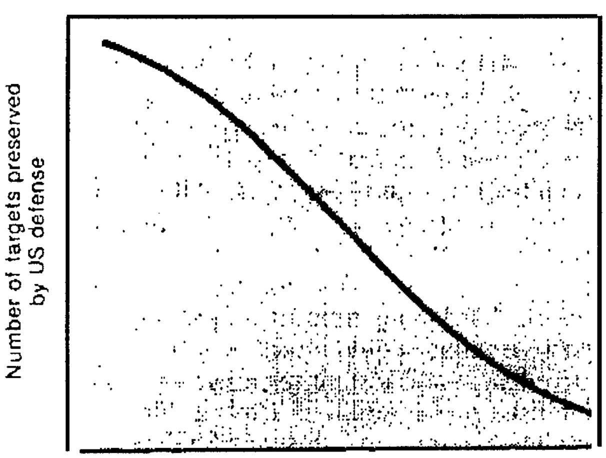

Fig. 5.1. Schematic drawdown curve, showing how the performance of a BMD system degrades as the size and sophistication of the attacking force increase.

Figure 5.2

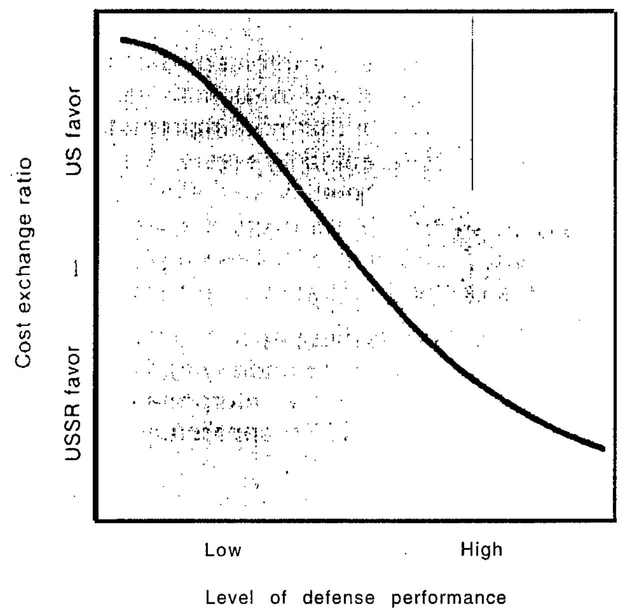

Fig. 5.2. The marginal cost exchange ratio measures the outcome of a race between the Soviet offense to enhance its penetration and a U.S. defense to maintain its level of protection. In general, modest defense goals (e.g., "preserve 40 percent of the targets") are easier to sustain than high goals ("preserve 95 percent of the targets") against improvements in Soviet offensive forces, including deployment of countermeasures.

The first analysis would be expressed in a drawdown curve such as that shown in figure 5.1. The Soviets can overcome the defense and destroy a large number of U.S. targets, but to do so the Soviets must "pay" an "attack price."

The second analysis would be encapsulated in the cost exchange ratio. The marginal cost exchange might be defined as follows: "Assume that in the year 2000 the U.S. defense and Soviet offense have evolved so that each has a certain level of effectiveness. Suppose the Soviets wish to improve their position and the U.S. resolves to maintain the status quo. Which side spends more in the competition?" For example, suppose every time the Soviets add 100 ICBMs to their arsenal, the United States has to add 20 satellites to its defensive constellation to intercept them: Which costs more, 100 ICBMs or 20 satellites?

In general, high levels of defense performance are harder to enforce in the face of offensive improvements than low levels: this important fact is shown schematically in figure 5.2 (see also Section 8.2).

All of the boost-phase intercept schemes discussed in this report are in such an early stage of conceptualization that nothing remotely like the analyses represented by Figures 5.1 and 5.2 can be done for them. Nonetheless, countermeasures are known for every boost-phase system devised, and in many cases simple heuristic estimates of the cost tradeoffs are **suggestive.**,

Technical experts disagree not so much about the facts and calculations underlying these countermeasures as about the interpretation to be given to them. Should an apparently fatal flaw uncovered at this early stage of study of a defensive concept be decisive, or should work (and the inevitable expectations that accompany it) continue on the chance that a new idea will turn up to rescue the concept? Would the Soviets really resort to a subtle tactic or exotic piece of hardware as a confident basis for their nuclear policy? Some analysts see BMD as a way of "forcing" the Soviets to take a certain direction in their pursuit of the arms race, e.g., away from large, slow-burning MIRVd boosters to single-warhead Midgetman-like boosters. In this view, defeat of the BMD is purchased at the price of a theoretically more stable and desirable Soviet offensive posture. All these questions of judgment loom large in making a final assessment of a given countermeasure.

5.1 ANTI-SATELLITE (ASAT) ATTACK, INCLUDING DIRECTED-ENERGY OFFENSE

All boost-phase intercept BMD concepts have crucial components based in space. Even a pop-up defense would need warning and very probably target acquisition sensors on satellites over the Soviet Union. Ground-based laser defenses would have mirrors and sensors—their most fragile components—in space. Vulnerability of these satellites is a cardinal concern because their orbits are completely predictable (they are in effect fixed targets), they are impractical to harden, conceal, or proliferate to any significant degree, and because successful development of effective directed-energy BMD weapons virtually presupposes development of potent anti-satellite (ASAT) weapons. ASAT is the clear boost-phase analogue of familiar defense suppression tactics against traditional BMDs, where attack is first made upon the defensive deployment (especially fixed radars) and then upon the defended targets.

The interplay of ASAT techniques–missiles (nuclear or conventional), space mines, directed energy—and satellite defense (DSAT) techniques is a complex one, It is difficult to generalize, but in the specific case of large battle stations in low-earth orbit it would seem that the advantage is very likely to lie with ASAT, not DSAT. For one thing, the offense need not destroy a large number of defensive satellites, but only "cut a hole" in the defensive constellation. Second, the traditional military refuges all offer complications: concealment from radar, optical, infrared, and electronic detection, while possibly successful for small payloads in supersynchronous orbits, is impractical for large, complex spacecraft at most a few thousand km from the earth's surface; decoy satellites must generate heat, stationkeep, and give status reports, and they are in any event only useful if the ASAT designer is somehow restrained (perhaps by cost) from shooting at all suspicious objects; hardening imposes weight penalties, and massive shields could interfere with the constant surveillance and instant response required of the defense; proliferation is useless for expensive satellites facing inexpensive ASAT methods, As a consequence, discussions of DSAT for BMD battle stations usually emphasize large keep-out zones around the satellites and active self-defense. A third reason why ASAT is likely to prevail over DSAT is that possession by the offense of the same type of directed energy satellites used by the BMD probably assures successful first

strike. Fourth, the Soviets would pick the time and sequence of their attack, and it would occur over Soviet territory.

Two rather novel ASAT threats are worthy of note. The first is the x-ray laser itself. The x-ray laser, if it could be developed, would constitute a powerful space mine. Because of its long range, it could lurk thousands of km from its quarry. The Soviets might also launch x-ray lasers a few seconds before launch of their main attack. Recall that the well-known phenomenon of bleaching (see Section 3.3) would probably allow such x-ray lasers to shoot out of the atmosphere at a U.S. x-ray laser defense, but the U.S. x-ray lasers could not shoot down into the atmosphere at the ascending lasers.

A second ASAT tactic, discussed for many years, imagines the Soviet Union exploding nuclear weapons at high altitudes in peacetime with the intent of shortening the orbital lifetimes of the U.S. defensive satellites, The nuclear bursts inject further radiation into the van Allen belts that circle the earth's equator from about 1,500 to 10,000 km altitude. Satellites (more likely carrying sensors than weapons at these altitudes) passing through the belts accumulate a radiation dose that gradually degrades electronics, sensors, and optical surfaces. This possibility, if taken seriously, would require defensive satellites designed to withstand rather substantial accumulated radiation doses.

A detailed treatment of the ASAT problem is beyond the scope of this Background Paper. The following "parable" illustrates some of the problems encountered in trying to ensure the survivability of a defensive constellation, taking the 20 MW HF lasers of Section 3.1 as an example.

The United States deploys the HF lasers in this hypothetical system in low orbits at 1,000 km altitude. Higher altitude would place them too far from their targets. This is unfortunate: higher altitude (say, between 2,000 km and semisynchronous orbit at 20,000 km) would move the satellites further from ground-based ASAT weapons and put them into lesser-used orbits where staking out a sanctuary would involve less interference with foreign spacecraft.

Suppose the battle station designers have succeeded in the considerable task of making the satellites resilient to multi-megaton nuclear space mines (bombs, not x-ray lasers) as little as 100 km away, To keep all Soviet spacecraft (i.e., all potential mines) at least 100 km away, the United States claims for itself the orbital band between 900 and 1,100 km altitude. Perhaps the Soviets are awarded some other orbital zone for their own military purposes. The United States establishes the following rules in its zone: 1) No foreign spacecraft may transit the zone without prearrangement; 2) All transiting vehicles must remain at least 100 km from all U.S. battle stations, passing through a "hole" in the constellation; 3) Foreign spacecraft failing to obey these rules may be destroyed by the U.S. lasers.

Consider first a Soviet kinetic energy ASAT deployed at 1,100 km altitude, just outside the U.S. keepout zone. Suppose the rocket interceptors on the Soviet satellites have the same propulsive capacity—one km/see—as the proposed High Frontier Global BMD system. The Soviet ASATs are then just 100 seconds away from the U.S. lasers. The U.S. lasers must therefore be very vigilant to avoid surprise attack. Fortunately, at 100 km range the 20 MW laser with 10 m mirror would burn up even a heavily hardened ASAT rocket in short order. Since starting up the main laser for self-defense might be awkward, wasteful of fuel, or time consuming, each U.S. battle station might be escorted by a satellite carrying a smaller laser or rockets for self-defense.

A constellation of Soviet 20 MW, 10 m HF lasers (the same technology as the U.S. lasers) at 1,100 km is another matter. These lasers could attack the U.S. lasers seconds before launch of a Soviet ICBM attack. The United States would have to keep these Soviet spacecraft ***thousands*** of km away from the U.S. constellation. That is, the United States would have to dominate near-earth space. Suppose the United States does so.

Now the Soviets build a fleet of pop-up x-ray lasers. These lasers climb to 100 km or so altitude, where information radioed to them from the ground allows them to point their rods at the U.S. lasers and detonate. The Soviets have had poor

success **at building an x-ray laser; theirs are 100 times less bright than the ideal x-ray laser described** in Section 3.3. Nonetheless, by pointing **all its lasing rods at the same target, a Soviet x-ray laser can destroy a U.S. laser battle station** at 10 Mm range. The U.S. chemical lasers attack the Soviet x-ray lasers as they ascend, but at this range long dwell times are required to destroy the Soviet lasers. By launching enough x-ray lasers simultaneously, the Soviets succeed in getting some to 100 km altitude, where they can shoot out through the thin atmosphere, before the U.S. lasers can destroy them. In this way, the Soviets "punch a hole" in the U.S. defensive constellation. (At a minimum, the Soviet ASAT attack consumes precious laser fuel aboard the U.S. battle stations.)

Just to make sure, the Soviets also deploy some powerful ground-based excimer or free electron lasers to destroy the U.S. battle stations as they orbit helplessly through space.

5.2 FAST-BURN BOOSTERS

Shortening the boost time and lowering the burnout altitude is easily accomplished at little sacrifice in useable ICBM payload (see Section 2). Shorter boost time increases the number of lasers needed for space-based laser or ground-based laser systems to handle simultaneously launched boosters. Short burn time makes rocket-propelled kinetic energy systems impractical, since the radius of action of each satellite becomes too small. Short burn time, together with low burnout altitude, would severely compromise the effectiveness of x-ray lasers popped up even from subs near Soviet shores. Low burnout altitude nullifies the neutral particle beam, which cannot penetrate very far into the atmosphere.

Fast-burn boosters would therefore be a potent, even decisive, countermeasure against almost all concepts for boost-phase intercept.

5.3 COUNTER C^3I TACTICS

Countermeasures to the crucial functions of target sensing and command and control are a relatively unexplored, but probably key, problem area for directed energy BMD. In the case of terminal and midcourse defenses, the issues of decoy discrimination, confusion caused by chaff and aerosols, radar blackout and infrared redout, radar jamming, and traffic handling have always been and remain central limitations, It is likely that analogues will be found for boost-phase systems. Devising countermeasures requires a degree of specificity about the nature of the defense system which cannot be provided in the present conceptual stage. There follow a few examples of C^3I countermeasures, by no means an exhaustive list.

A first point to note is that sensors are likely to be the most vulnerable part of a defensive satellite. A laser shined into an optical sensor can daze or injure the focal plane elements, though viewing in frequency bands absorbed by the atmosphere offers protection from ground-based lasers. Mirrors would be very susceptible to damage from a Soviet x-ray laser. A Soviet neutral particle beam could disrupt electronic circuits on U.S. satellites. Radiation pumped into the van Allen belts by nuclear bursts would affect sensors and electronics.

A single nuclear burst causes the upper atmosphere to glow brightly over areas 100 km in radius for over a minute. Calculated radiances[2] are large enough to cause background problems for MWIR tracking sensors.

[2]S. D. Drell and M. A. Ruderman, *Infrared Physics*, Vol. 1, p. 189 (1962).

Some directed-energy weapons produce spots only meters wide at the target, requiring target sensing to commensurate precision via laser radar (see Section 4.1). Laser radars sense laser light reflected from the target. A small corner reflector affixed to the target would produce a bright glint of reflected light, as would other corner reflectors launched on sounding rockets, ejected from the target, or attached to the target by expendable booms. These proliferated corner reflectors might force the beam weapon to attack them all.

The homing sensor of a kinetic energy interceptor could be susceptible to spoofing, depending on its type.

Jamming satellite-to-satellite communications crosslinks is probably ***not*** an effective offensive tactic, since the links would have narrow beamwidths, requiring the jammer to locate itself directly between the two satellites; and wide bandwidths, requiring high jammer power.

5.4 SHIELDING

A degree of shielding from lethal effects is practical for all but the kinetic energy weapons but involves in each case different methods suited to the different physical principles at work. At the same time, large uncertainties plague all lethality estimates, and further testing and study will be needed before firm answers can be given for any of the systems. For thermal kill with a laser, a solid booster designed with some attention to a laser threat can probably easily be made to withstand 10 kJ/cm^2. Application of a gram or so of heatshield material on each square centimeter of booster skin can probably triple this hardness, and spinning the booster enhances hardness by another factor of three. Heatshield material is ablative, meaning that when heated it burns off, carrying away the heat in the combustion gases rather than conducting it through to the missile ski n underneath. A factor of nine increase in hardness requires the defensive laser to dwell on the booster nine times as long or to approach within a third of the range, Though hardening a new booster from scratch is clearly easiest, there is no serious impediment to retrofitting ablative coatings on existing boosters. Applying a gram per square centimeter of ablative material to the entire body of the MX missile would require removing several RVs from the payload, since the coating would weigh well over 1,000 kg.

An interesting possibility, requiring further study, would involve injecting into the atmosphere or producing from atmospheric gases, either throughout the ICBM flyout corridors or in the vicinity of individual boosters, smoke or laser absorbing molecules. Likewise, dust clouds raised by ground burst weapons (delivered by cruise missiles or by ICBMs that "leak" through the defense) might cause serious propagation problems for the ground-based laser scheme,

Hardening to an x-ray laser involves quite different physical principles. Recall that the x-ray energy is deposited in a paper-thin layer of the booster skin. The superheated layer explodes, applying an impulsive shock to the booster. Obviously a paper-thin shield between the booster and the laser will stop x-rays from reaching the booster wall. But the problem then becomes the debris from the exploding shield. One can easily show by calculation that the debris applies virtually the same impulse to the wall of the booster as would result from direct impinging of the x-rays! A number of schemes can be devised to divert the debris from striking the booster, but these require more study to implement in practice. One factor acting in favor of the shield designer is that the booster is not vulnerable to x-ray attack until it leaves the atmosphere. The lightweight shields therefore do not have to be designed to suffer large drag forces.

The neutral particle beam presents a third distinct type of hardening problem. The energetic beam particles penetrate into the target, and several centimeters of lead would be required to stop them. Since the beam cannot penetrate very far into the atmosphere, only the upper booster

stages need be hardened. But if the third stage, say, of the MX were covered with a few grams per square centimeters of lead, the shielding alone would weigh as much as several RVs. On the other hand, if the neutral particle beam is only designed to disrupt or damage sensitive electronics, but is not powerful enough to do damage to other parts of the missile, only the sensitive components need be shielded. The weight penalty then becomes small.

It is possible that the offense can extend the protection of the upper atmosphere against the neutral particle beam by exploding a few nuclear weapons at moderate altitudes before the beam can reach them. The detonations heat the air, which rises, effectively elevating the altitude at which the neutral beam is stripped of its remaining electron and bent in the geomagnetic field. This phenomenon is called atmospheric heave. It is as yet unresolved whether atmospheric heave will loft enough air to make a difference to the engagement altitude of the x-ray laser.

5.5 DECOYS

There is no way for a decoy booster to mimic closely the hot exhaust plume of an ICBM booster except by burning a similar rocket stage. One can add chemicals to the propellants to brighten a small booster's plume and dim the ICBM's, but as a first approximation a faithful decoy must be another booster.

Decoy tactics are therefore not as attractive for boost-phase intercept systems that use plume sensing as they are for midcourse and reentry defenses, where large numbers of cheap, lightweight decoys can be carried with negligible offload of RVs. Still, the usefulness of a decoy depends not on how expensive the decoy is, but on how the cost of the decoy compares to the cost of the defense that intercepts it. Booster decoys **would not be nearly as expensive as true** ICBMs, since they carry no warheads or precision guidance system, they need not be highly reliable, and they might **not need to be based in** underground silos but can be deployed above ground next to the ICBM silos.

Some of the boost phase intercept systems must grow in the number of their deployed battle stations in direct proportion to the number of Soviet boosters. Deploying one decoy (with a dummy payload) next to each of the 1,400 Soviet ICBM silos might cause the United States to have to double the number of battle stations overhead (and thus worldwide, multiplying by the absentee ratio) to handle the extra traffic. If the defensive battle stations were at all expensive, this would bean unpleasant prospect for the United States.

Many directed energy schemes would not rely on plume sensing alone (see Section 4.1). Decoy tactics against laser radars (including corner reflectors; see Section 5.3) might be much easier for the offense to implement than mimicking the booster plume.

5.6 SALVO RATE

The worst-case attack for all the boost-phase intercept schemes is massive, simultaneous launch of all Soviet ICBMs. The defensive satellites over the Soviet silo fields at the moment of launch then have to handle the entire attack.

A more leisurely salvo rate would allow laser and particle beam defenses that have to dwell on their targets more time to handle more targets. Slow attack also allows pop-up defenses to climb to intercept position. An attack drawn out 10

minutes or longer allows fresh defensive satellites to move along their orbits into position overhead, replacing depleted satellites. The orbital period of satellites in low earth orbit is about 90 minutes. If there are 8 to 10 satellites in each ring of the defensive constellation, satellites replace one another every 10 minutes or so.

An exception to this simultaneous-launch worst-case analysis is the x-ray laser, which delivers all its energy in an instant.

There would seem to be few military penalties for the Soviet Union to adopting plans to launch all their ICBMs in large attack within a few minutes. Indeed, if one of their objectives is to destroy U.S. ICBMs in their silos, rapid attack would be the best Soviet choice. Some, though not all, of the successful attacks that could be mounted on Closely Spaced Basing (Densepack) for MX involve very slow or intermittent salvo rates, however.

More importantly, in many circumstances the Soviets might wish to launch only a traction of their ICBM force. A U.S. defense deployment too small to intercept all boosters in a massive attack would still be able to handle a small attack. A light defense might therefore establish a "threshold" of attack intensity below which Soviet boosters would face intercept. This prospect is discussed further in Section 9.

5.7 OFFENSIVE BUILDUP

The most straightforward way for the offense to compete with the defense is to grow in size. If for every new ICBM added to the Soviet arsenal, the U.S. defensive satellite constellation must be augmented at comparable or greater cost, the Soviets could challenge the United States to a spending race to their net advantage. On the other hand, if the defensive buildup is cheaper than the offensive buildup, the defense forces the offense either to accept limitations on its penetration or to resort to qualitative changes in its arsenal.

As an illustrative example of such a cost tradeoff, consider the hypothetical H F chemical laser system described in Section 3.1. Each laser in that system requires 1.7 seconds of dwell time to destroy a booster. During the 200 seconds of boost, each laser overhead can therefore destroy 120 boosters. But for each laser overhead, 32 are needed worldwide. Suppose now that the Soviets deploy, in one region of the U. S. S. R., 1,000 Midgetman missiles at a cost of 10 to 20 billion U.S. dollars (see Section 2). The U.S. defense now needs to be "beefed up" with addition of (1 ,000)X (32)/120 = 270 laser battle stations. A tradeoff of more than one complex U.S. satellite, launched and maintained on orbit, for every 4 Soviet boosters (or decoy boosters) deployed on the ground would certainly appear to be a losing proposition for the United States. This is true even though the hypothetical HF laser system represents a very favorable outcome of laser technology.

Note that Soviet deployment of new ICBMs in one region of the Soviet Union, within coverage of only a single U.S. satellite, gives them the best leverage in the cost exchange.

5.8 NEW TARGETING PLANS

Truly efficient ICBM defenses would presumably force upon the superpowers a stricter attention to targeting priorities. With thousands of warheads in today's arsenals able to be literally lobbed into any target area unimpeded, the superpowers have less need to be discriminating or parsimonious in their nuclear targeting. Such a shift might have both desirable and undesirable

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consequences. For example, the offense might decide that in view of the cost of countermeasures it could no longer afford to threaten the other side's ICBM silos. The warheads "freed up" from the countersilo mission might then be dedicated to heavier targeting of other aim points (per**haps cities) as a hedge against poor penetration.** How the superpowers would greet these hypothetical defenses is not clear, but it is probably quite wrong to imagine future defenses acting against offensive forces targeted according to the war plans of today.

5.9 OTHER MEANS OF DELIVERING NUCLEAR WEAPONS

One additional Soviet response to an efficient defense against their ICBMs would be increased emphasis on submarine-launched ballistic missiles (SLBMs), bombers, cruise missiles, and whatever novel methods time and ingenuity might in the future devise for introducing nuclear weapons to the United States. As defenses forced up the cost-per-delivered-warhead of ICBM forces, these other methods would become relatively more attractive. Though they would sidestep the BMD, these delivery means have higher pre-launch survivability than ICBMs, and bombers and cruise missiles have longer times of flight, These attributes are usually seen as "stabilizing." Shifting the emphasis of the arms competition away from ICBMs is therefore sometimes viewed as adequate payoff for the BMD effort.

SLBMs would obviously be vulnerable to the same boost-phase weapons as ICBMs. The same worldwide coverage, reflected in the absentee ratio, that plagues the anti-ICBM cost exchange means that orbiting boost-phase defenses threaten SLBMs the world over. However, midcourse and terminal tiers of a layered defense would in general have much less capability against SLBMs, because of the latter's short time of flight, possibly depressed trajectory, and uncertain direction of attack. Thus SLBMs could conceivably enjoy greater penetration of a layered defense than ICBMs.

If one takes an optimistic view of emerging defensive technologies, or if one contemplates technological "breakthroughs," it is at least conceivable that such developments will spawn new ways of delivering or aiding the delivery of nuclear weapons as well as new ways of interdicting them.

Section 6

A WORD ON “OLD” BMD AND “NEW” BMD

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No one knows whether directed-energy weapons can be built with the characteristics assigned to the hypothetical systems of Section 3. Even if such systems can be built, it is not clear that their performance will match, much less exceed, the performance of terminal and midcourse BMD systems in level of protection (attack price) and in cost relative to offsetting offensive improvements. The boost-phase BMD systems receiving so much attention today were a year ago at the periphery, to say the least, of technical discussion of missile defense. It is important not to lose sight of the status of traditional reentry and "advanced" (as they were called a year ago) "overlay" midcourse BMDs.

Naturally, the promise of the better-understood terminal and midcourse systems does not seem so grandiose, nor the flaws so clear-cut, as they do for the conceptual boost-phase defenses discussed in this Background Paper. Sounder technical assessments can be made of the "old" BMDs than of the "new" concepts. Rough concepts gloss over all the difficult design problems that inevitably limit achievable performance and turn up serious problems; nonetheless, identifying potentially unsolvable problems at this early stage of study does not mean they will remain insurmountable. BMD architectures incorporating boost-phase intercept are not known to be able to perform better, dollar-for-dollar, than BMD architectures incorporating only midcourse and reentry intercept. They are just not known to be worse. Terminal defense systems have been studied, designed, and tested for years, and it is generally agreed that such systems, acting alone, can enforce a modest attack price of between 2 and 8 RVs (perhaps equivalent to 20 to 80 percent of a booster) per defended aim point. Though their capabilities are modest, reentry and midcourse defenses suffice for modest defensive goals. There is no need to incur the technical risk of "new" boost-phase intercept schemes unless one aspires to levels of performance clearly beyond those possible with "old" concepts.

Many of the "new" concepts for boost-phase intercept are not new at all. They have been studied and discussed in one form or another for 20 years. Conversely, there are some new ideas for improving terminal and midcourse BMDs.[1] The spirit of technical optimism that accompanied the new emphasis on boost-phase intercept in the past year affected thinking about "old" BMD as well.

For terminal defense systems, the new features receiving attention are, first, non-nuclear warheads on interceptor missiles and, second, airplane-borne infrared sensors as supplements to ground-based radars. The principal benefit of non-nuclear intercept is that interceptors can be deployed nationwide without public concern about the safety of defensive nuclear warheads. Non-nuclear kill does not permit the defense to avoid all the disruptive effects of nuclear bursts, however, since the offense can still arrange for RVs to detonate when they sense interceptor impact ("salvage fuzing"). The miss-distance/weight relationship of the non-nuclear warhead requires the interceptor to approach more closely to the RV, and this in turn requires a homing seeker on the interceptor. Terminal homing obviously creates new opportunities for offensive countermeasures.

Airborne optical sensors obviously do not suffer radar blackout, but they can suffer the analogous problem of infrared redout. Decoy discrimination remains a problem, though it acquires some interesting new features. Details of these new aspects of terminal BMD are obviously classified. Though important, these aspects are fairly straightforward extensions of traditional techniques rather than revolutionary "breakthroughs."

New thought about midcourse defense focuses on alleviating the Achilles' heel of systems that use infrared sensing to support intercept in space: the ease with which the offense can accompany attacking RVs with clouds of decoys. One approach receiving attention is simply to cheapen the interceptor and shoot at everything, RVs and decoys alike. Another is to probe the attacking

[1] See Julian Davidson, "BMD: Star Wars in Perspective," *Aerospace America*, January 1984, p. 78.

objects with an active sensor, rather than relying on their thermal emissions, in the hope of discriminating RVs from decoys. Some of these "active discrimination" schemes are complex and expensive and might in turn be susceptible to offensive spoofing. A third aid to discrimination is the boost-phase defensive layer itself, which might constrain the number and type of penetration aids the offense could mount on each booster in addition to reducing the total number of objects approaching the midcourse tier. Fourth, extensive use of space-based sensors would allow the defense to observe penetration aids throughout their flight (including during deployment from the bus) rather than just as they approach the United States. It remains unclear whether these techniques will be worth the costs and new countermeasures they would bring to the defense.

Section 7

A HYPOTHETICAL SYSTEM ARCHITECTURE

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Most analysts of boost-phase BMD assume that midcourse and terminal BMDs will augment the boost-phase layer. This section assembles a hypothetical layered defense system ***in toto.*** This system is pure/y ***illustrative,*** taking current BMD concepts at their face value and conveying a concrete image of the defensive architectures analysts apparently have in mind when they speak of nationwide defense. Obviously there are many choices for such a "strawman " system. The particular system described below was chosen for its illustrative value and not because it represents some "most plausible" alternative. It would be meaningless to suggest a "front runner" in the present state of study and technology development. Rather, the purpose of this example is to show how the layers interact and to indicate the overall scale of the deployments contemplated, without implying that anything remotely like it ever could or would be built.

A defense with several layers presents the offensive planner with some of the variety of problems that afflicts the BMD designer, who never knows in advance which attack tactic or countermeasure the offense will choose and must include responses to all of them in the system design. Layered defense forces the offense not only to develop responses to all the layers, but to develop responses that can be accomplished simultaneously. Thus, for example, the method chosen to avoid boost-phase intercept must not prevent deployment of lightweight midcourse decoys. The synergistic effect of the several layers obviously works strongly in the defense's favor.

Nonetheless, one must compare the performance of a three-tiered defense to the performance of a two-tiered defense of the same cost. Thus it should be no surprise if a $200 billion system with boost (and possibly even post-boost), midcourse, and terminal layers performs better than a $50 billion system with no boost phase layer. The correct questions are whether the additional $150 billion is worth the extra performance, and whether spending the $150 billion on more terminal and midcourse defense would in fact be a better investment.

Occasionally one sees a simplified leakage calculus applied to layered defense. The calculus assigns a "leakage" of, say, 25 percent (0.25) to the boost phase layer, 15 percent to the midcourse layer, and 10 percent to the reentry layer, deducing an "overall leakage" of 0.4 percent on the basis of the equation $(0.25) \times (0.15) \times (0.10) = 0.004$. Though the term leakage can be defined so that this calculus holds, the result actually bears little relation to the number of targets preserved by the defense. For one thing, a given defensive layer does not have an associated leakage ***fraction*** independent of attack size: the leakage fraction for each layer usually increases with attack size, most obviously (but not only) when the defensive arsenal becomes saturated. Second, the performance levels of the individual layers are not independent. For example, if the midcourse layer's interceptor arsenal is sized to handle only 25 percent of the attack, and the boost-phase layer works poorly and in fact allows 50 percent of the attack through, the midcourse layer obviously cannot display the same fractional efficiency against the attack of double the expected intensity. Conversely, improvements in one layer might improve performance of another: effective boost-phase or midcourse layers might force the offense to abandon the highly structured "laydowns" of RVs in space and time that limit a terminal layer's effectiveness. Third, the raw number or fraction of leaking RVs does not indicate the number or fraction of targets destroyed because of the tactics of preferential offense and defense. For these reasons, the leakage calculus is not a helpful way to encapsulate layered defense performance.

7.1 SYSTEM DESCRIPTION

The system design described below takes literally the goal of comprehensive nationwide defense. It seeks the capability (at least on paper) to engage all attacking Soviet missiles, whether targeted at cities, U.S. silos, or other military installations. Clearly the precise numbers and kinds of components in this description can be adjusted to suit any set of assumptions. The point of this description is merely to convey the flavor of these massive architectures. Most assumptions are favorable to the defense.

Suppose that at some time in the future the Soviet ICBM arsenal still consists of 1,400 boosters, as it does today. For simplicity, suppose further that each booster is an MX-sized solid propellant missile carrying 10 RVs and that all silos are located in one large region of the U.S.S.R. The boosters are not specially shielded against lasers, but some care in their design has given them an effective hardness of 10 kJ/cm^2, and they are further spun during ascent. Each booster carries a small number of decoys, but their small number is offset by the decoys' high fidelity. Each RV is accompanied by 9 lightweight infrared replicas and 1 high altitude reentry decoy. (This is a very modest penetration aid loading. One can assume larger numbers with perhaps poorer fidelity, chaff and aerosols, etc.)

The hypothetical U.S. defense system comprises both HF chemical laser battle stations and x-ray laser battle stations for boost-phase intercept, land-based midcourse interceptors carrying LWIR homing vehicles (the so-called "Overlay"), and land-based high-endoatmospheric homing interceptors with non-nuclear warheads for reentry intercept.

Table 7.1.—Hypothetical Future U.S. Defense Designed for Nationwide Protection Against Hypothetical Future Soviet Offense

U.S. Defense	Soviet Offense
5 warning satellites	1,400 MX-like ICBMs deployed in one region
180 HF laser satellites	10 RVs per ICBM
180 laser radars	9 midcourse decoys per RV
900 x-ray laser satellites	1 reentry decoy per RV
900 MWIR trackers	
28,000 midcourse intercept vehicles and boosters	
20 LWIR satellites	
75 radars	
140,000 terminal non-nuclear interceptors	
25 aircraft with LWIR sensors	

SOURCE: Author.

The HF chemical laser system resembles that described in Section 3.1, except that it has only five 20 MW lasers at each position in the 32-position constellation, for a worldwide total of 160. At a range of 2 Mm, a laser must dwell on each spinning booster for 5 seconds, so each laser at this range can handle 30 simultaneously launched boosters if defense begins 30 sec into the 180 sec boost phase of an MX-like booster. The five lasers overhead the Soviet silos at any one time can therefore only handle 150 of the 1,400 Soviet ICBMs. For small Soviet attacks, however, this non-nuclear boost-phase layer suffices.

For a large-scale Soviet attack, the United States deploys in addition a nuclear boost-phase system of x-ray lasers. A "perfect" laser with characteristics such as those derived in Section 3.3 can intercept ideally about 50 boosters at 4 Mm range. Therefore 28 lasers need to be in position over the Soviet silos at any time to handle a massive launch, giving a worldwide total of 900 (absentee ratio 32).

Warning for the boost-phase system is provided by MWIR warning satellites in synchronous or supersynchronous orbits. **Also, each** of the 160 HF laser battle stations has an MWIR telescope with 4 m mirror and an ultraviolet or visible ladar with 2 m mirror for pointing. Each x-ray laser is accompanied by an MWIR telescope tracker with 1 m mirror.

The 1,400 Soviet boosters carry 14,000 RVs, 126,000 midcourse decoys, and 14,000 reentry decoys. The United States assumes that only 10 percent of the boosters will survive the boost phase defense, so the midcourse tier needs to face 1,400 **RVs and 12,600 midcourse decoys. The midcourse interceptors are given extremely long range, so only two bases are needed to cover the entire United States. However, each base must be prepared to absorb the entire attack, since the Soviets could target one half of the country more heavily than the other. There-**

fore the United States needs 14,000 midcourse interceptors at each base, for a total of 28,000 interceptors. A constellation of 20 satellites with large LWIR sensors provide long-range acquisition and target assignment to these interceptors.

The United States next estimates that 90 percent of the RVs that enter the midcourse layer will be successfully intercepted. The terminal defense must handle 140 RVs plus 140 reentry decoys.[1] The reentry decoys are, by assumption, completely faithful in mimicking the signatures of RVs as seen by ground-based radars and aircraft-borne infrared sensors during early reentry—large decoy numbers have been sacrificed for this high fidelity. If the U.S. defense takes literally its charge of nationwide defense, it must be prepared to make 280 intercepts anywhere in the country.

[1] The number of reentry decoys the terminal system must face actually depends on whether the decoys fool the midcourse as well as the terminal system's sensors and on whether the terminal and midcourse layers cooperate in discrimination. Suppose first that the reentry decoys look like RVs (and therefore also like midcourse decoys) to the midcourse layer's sensor. Then the midcourse layer will Intercept 90 percent of them (more midcourse interceptors must be bought to do this). If, on the other hand, the midcourse layer correctly identifies the reentry decoys as non-lethal objects, it might (a) not intercept them, requiring the terminal layer to plan to face 140 RVs plus 1400 reentry decoys, increasing enormously the required arsenal of terminal interceptors; (b) intercept them, in which case a reentry decoy is a perfect midcourse decoy, making possible a new threat–large numbers of midcourse decoys that look like reentry decoys rather than RVs; (c) radio the information, object-by-object, to the terminal defense fields.

Each terminal defense site consists of a phased-array radar and a number of high altitude non-nuclear interceptors. Additional target acquisition support is provided by a fleet of aircraft patrolling the U.S. periphery, carrying LWIR sensors. Each radar has a radius of action of over 200 km, so 75 or so cover the entire United States. However, an interceptor only covers an area about 50 km in radius. Since the area of the United States is about 8 million square km, over 1,000 interceptor sites would be needed for nationwide coverage. Should the defense have to reckon with intensive Soviet attack on some regions and no attack on others? Clearly, yes. But equipping each interceptor site to handle all 280 objects passing through the first two layers would require buying 280,000 interceptors! The defense would need to buy this many interceptors if it wanted to claim the literal capability to engage ***all*** Soviet RVs, ***no matter*** where they landed. Suppose, then, that the United States hopes for a more evenly distributed Soviet attack and deploys just half of the arsenal needed for complete coverage— 140 interceptors per region. One radar might not suffice to handle all the RV traffic in its sector if the Soviets attack some sectors preferentially, but the United States nonetheless buys just 75 radars. Five aircraft on patrol at all times requires a backup fleet totalling perhaps 25.

Table 7.1 summarizes the offensive and defensive deployments.

7.2 ASSESSMENT

It is obviously not possible to assess the performance of a system, such as the hypothetical layered defense described above, whose components are not (and in many cases cannot be) designed today, much less assembled in an overall architecture. It is nonetheless worth sketching, in the illustrative spirit of this section, the issues that would require analysis if anything resembling Table 7.1 were ever proposed for deployment.

The first issue concerns the cost of the improvements to the system needed to offset growth in the Soviet ICBM arsenal—that is, the cost exchange ratio. The number of defensive weapons is proportional to the number of Soviet ICBMs. If the Soviets were to double the size of their ICBM arsenal, the United States would need to double the number of its x-ray lasers and interceptor missiles. (The number of sensors would generally have to increase also, though perhaps not in proportion to the Soviet buildup. The number of HF lasers could remain the same if the United States continued to intend to use this non-nuclear boost-phase layer to engage only Soviet attacks of 150 boosters or less.) Comparison of the two columns of Table 7.1 indicates that an arms race of Soviet offense and U.S. defense seems certain to favor the Soviet side greatly.

A second issue concerns the huge inventories of midcourse and reentry interceptors needed for nationwide defense. The arsenal of reentry interceptors shown in Table 7.1 is in fact only half the size needed for literally complete nationwide coverage, as remarked above. The cause of these large interceptor inventories–besides the obvious presence of decoys–is twofold: first, the low leakage sought by the defense precludes preferential defense, the tactic that makes silo defense so much more economical; and second, the limited coverage of each interceptor battery makes preferential ***offense*** possible for the attacker. The goal of nationwide low-leakage defense therefore forces the BMD system to forfeit the two sources of leverage that have historically impelled BMD towards the technically modest mission of defending compact silo deployments to relatively low survival levels.

Soviet countermeasures–besides straightforward buildup of ICBMs—is a third issue. The particular boost-phase layers described above are susceptible i n varying degrees to all of the countermeasures described in Section 5, and the midcourse and reentry layers to their respective sets of countermeasures.

Defensive coverage against submarine-launched ballistic missiles (SLBMs) is a fourth issue. The boost-phase layers can intercept SLBMs launched from all points on the globe. Though the average range from laser satellite to booster is larger at equatorial and polar latitudes than at the mid-latitudes where Soviet ICBMs are located, the number of SLBMs that could be launched in a short time from each ocean area is also much smaller than the huge number of ICBMs that could lift off simultaneously from the U.S.S.R. Even the chemical laser deployment alone might suffice for boost-phase coverage of SLBMs. The midcourse and reentry layers, however, would in general not perform as well against SLBMs as against ICBMs. SLBM trajectories present bad viewing angles to the midcourse layer's LWIR sensors, and the short timeline limits interceptor coverage. The reentry layer would need to be augmented with more airborne sensors and more radars (or radar faces) to cover attack from the ocean. In general, then, a layered system optimized for ICBM defense could not necessarily handle SLBMs as well.

Section 8

DEFENSIVE GOALS 1: THE PERFECT" DEFENSE

DEFENSIVE GOALS 1: THE PERFECT DEFENSE

No assessment of whether a defensive system "works" or not is meaningful without a clear and direct statement of the goal of the deployment. Though there has been much discussion of the feasibility of boost-phase BMD, proponents and skeptics alike frequently leave unstated the standards against which they are judging the technical prospects. A "successful" BMD deployment could be defined as anything from a truly impenetrable shield, to a silo defense that merely costs less to build than it costs the Soviets to overcome, to a tangled deployment that just "creates uncertainty" for the attacker.

The most ambitious conceivable goal for BMD would be to take at literal face value the words of President Reagan in his so-called "Star Wars" speech of March 23, 1983, when he called for development of a defense capable of making nuclear weapons "impotent and obsolete."[1] It is not clear that the President intended his words to be taken literally, nor that the Administration or anyone else is suggesting the United States seek a truly perfect or near-perfect defense.[2] Nonetheless, so much writing and debate focuses on this prospect, and its importance is so great, that it is taken up in this section. Section 9 treats the many other possible goals for less-than-perfect defenses.

There is some confusion in the literature about the use of the term "mutual assured destruction" (MAD) in connection with the notion of perfect defense. In common strategic parlance, MAD refers to the ***technological circumstance*** of mutual vulnerability to catastrophic damage from nuclear weapons, not to a ***chosen policy* to** promote such vulnerability. There is a strategic school of thought that advocates a policy usually called "minimum deterrence, " maintaining that the capability for assured destruction of Soviet society is the ***only*** requirement of U.S. strategic forces. However, many experts believe that effective deterrence and other national security objectives require nuclear forces capable of many other tasks than assured destruction. This section addresses itself to the question of whether MAD is an avoidable technological circumstance, ***not*** to whether minimum deterrence is a prudent strategic policy.

A sensible start at judging the prospect for near-perfect defense must involve two steps: first, an exact statement of what perfect defense means in the context of attack on society with nuclear weapons; second, some way of gauging the likelihood of success when the technological future cannot be accurately predicted.

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[1] *Weekly Compilation of Presidential Documents*, Vol. 19, *No.* 12, March 28, 1983, pp. 447-448, The text of the relevant part of the speech is reprinted as Appendix A.

[2] Defense Secretary Caspar Weinberger appeared to confirm a literal interpretation in a March 27 interview on NBC's *Meet the Press*, when he said (as reported in the *Baltimore Sun*, March 28, 1983, p. 1).

> The defensive systems the President is talking about are not designed to be partial What we want to try to get is a system which will develop a defense [SIC] that is thoroughly reliable and total, I don't see any reason why that can't be done.

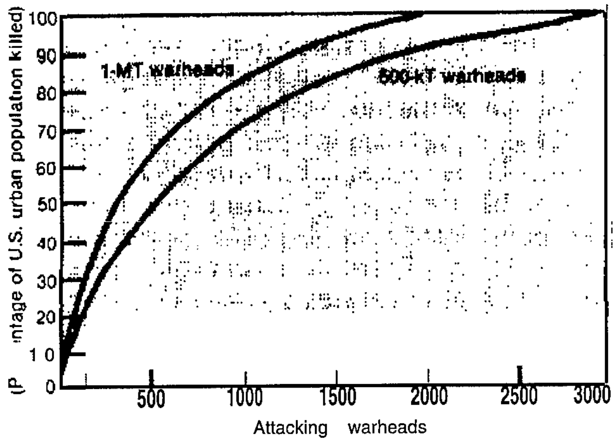
Later, the Defense Department stated that the purpose of the President's initiative was not to save lives, but to deter war. Responding to the "Congressional Findings" section of the proposed "People Protection Act" (H.R. 3073, 98th Congress, 1st session) which stated, "The President has called for changes in United States strategic policy that seek to save lives in time of war, " Defense Department General Counsel William H. Taft IV wrote:

> **It is clear that portions of the "Congressional findings" section [of H R 3073] vary from the purpose of the President's initiative First, and most importantly, the purpose of the President's initiative is to strengthen our ability to deter war by, as the President has said, "rendering [ballistic missiles] impotent and obsolete. In short, the purpose of the Administration's policy is to reduce the likelihood of war. The finding [of H.R. 3073] that the purpose is to "save lives in time of war' departs from our goal of deterring war**

Dr. Charles Townes, a frequent adviser to Secretary of Defense Weinberger and leader of two DOD task forces studying basing modes for the MX missile, said that a perfect defense proposal is "quite impractical. There is no technical solution to safeguarding mankind from nuclear explosives. (New *York Times*, April 11, 1983, p. 14).

8.1 NUCLEAR ATTACK ON SOCIETY

Figure 8.1 .-The Effect of Attack Size on the Extent of Prompt Fatalities in U.S. Urban Areas



Note: Aimpoints chosen to maximize prompt human fatalities. U S. urban population is estimated to be 131 million, as in the 1970 census.

SOURCE. Arms Control and Disarmament Agency, U.S. *Urban Population Vulnerability* (ACDA, 1979), quoted in Arthur M. Katz, *Life After Nuclear War: The Economic and Social Impacts of Nuclear Attacks on the U.S* (Ballinger, 1982) Adapted from Ashton Carter and David N. Schwartz, eds , *Ballistic Missile Defense* (The Brookings Institution, 1984), p 168

Suppose one wants to take literally the goal of removing from the hands of the Soviet Union the ability to do socially mortal damage to the United States with nuclear weapons, so that the Soviet Union no longer possesses the elemental capability of assured destruction.) What does this mean?

Figure 8.1 shows how the percent of the U.S. urban population (about 130 million people in the 1970 census) killed promptly increases with the number of Soviet warheads detonating over U.S. cities. No such curve of the effects of nuclear attacks on cities should be taken as anything but suggestive: uncertainties are very great in such estimates, and no attempt has been made to reflect long-term and indirect effects of the detonations.[3] The curve also accounts only for fatalities, not for the many additional people injured. If one wishes to account for the possibility of civil defense evacuation, then the curve should be taken to represent not the number of people killed, but the number of people whose homes, businesses, historic monuments, schools, and places of worship have been destroyed.

No one supposes that the Soviet Union actually chooses aim points for its nuclear weapons with the goal of maximizing human fatalities, as has been done in preparing Figure 8.1. if the United States possessed a defense capable of intercepting all but a few of the 8,000 to 10,000 Soviet nuclear warheads, however, the Soviet Union might retarget its forces to wreak the most destruction possible with its few penetrating warheads. At any rate, any defense promising U.S. society genuine immunity from nuclear attack must reckon with Soviet determination to keep its arsenal from being "rendered impotent, " and therefore with targeting plans contrived to do the most damage to the fabric of U.S. society.

Where on the curve of Figure 8. 1–after how many detonations—does one locate the boundaries of "assured destruction, " "assured survival," "impotent and obsolete, " and similar phrases? Clearly there is no analytical prescription for these boundaries: they are the subject of **a broader human judgment. 500 half-megaton warheads kill half the urban population, injure most of the rest, and totally destroy all American cities and large towns. Just 5 megatons, about one two-thousandth of the Soviet arsenal, detonated over the 10 largest U.S. cities could kill several million people and wound over 10 million more.**

For the sake of discussion, we shall use 100 megatons—about 1 percent of the Soviet Union's arsenal and 1.5 percent of its ICBM force—as the level of penetration for which a defense would

[3]For discussion of some of the effects of nuclear weapons on population and cities, see: U.S. Arms Control and Disarmament Agency, *An Analysis of Civil Defense in Nuclear War* (ACDA, 1978); OTA, *The Effects of Nuclear War* (GPO, 1979); ACDA, *The Effects of Nuclear War* (ACDA, 1979); **"Economic and Social Consequences of Nuclear Attacks on the United States, " prepared for the Joint Committee on Defense Production, 96 Cong. 1 sess., 1979;** J. Carson Mark, "Global Consequences of Nuclear Weaponry, " *Annual Review of Nuclear Science*, Vol. 26 (1976), pp. 51 -87; **National** Research Council, *Long-Term Worldwide Effects of Multiple Nuclear- Weapons Detonations* (National Academy of Sciences, 1975).

be judged "near-perfect." This definition is obpiously very generous to the notion of perfect defense, since most people would presumably not regard 100 megatons of explosive force as "impotent and obsolete. " Still, it is a definite reference for assessment.

8.2 THE PROSPECTS FOR A PERFECT DEFENSE

There is not and cannot be any "proof" that unknown future technologies will not provide near-perfect defensive protection of U.S. society against Soviet ICBMs. The question that needs to be answered is whether the prospects for near-perfect defense are so remote that such a notion has no place in reasonable public expectations or national policy. it is, after all, not provable that by the next century the United States and U.S.S.R. will not have patched up their political differences and have no need to target one another with nuclear weapons. The issue of the perfect defense is unavoidably one of technical judgment rather than of airtight proof,

Four misapprehensions seem common among non-technical people addressing the prospects for perfect defense.

The first misapprehension is to equate successful technology development of individual devices—lasers, power sources, mirrors, aiming and pointing mechanisms—with achievement of an efficient and robust defensive ***system.*** Millionfold increase in the brightness of some directed-energy device is a necessary, but is far from a sufficient, condition for successful defense. In the early 1960's, intercept of RVs with nuclear-tipped interceptor missiles was demonstrated—"a bullet could hit a bullet''-but ***20*** years later systems incorporating this "kill mechanism" are still considered relatively inefficient. In general, skeptics about the future of space-based directed-energy BMD do not confine their doubts to, or even emphasize, unforeseen problems in developing the individual components.

A second misappprehension arises in attempts o equate BMD development to past technological achievements, such as the Manhattan project's atomic bomb or the Apollo moon landings. Q The technically minded will recognize a vital difference between working around the constraints imposed by nature, which are predictable and unchanging, and competing with a hostile intelligence bent on sabotaging the enterprise. A dynamic opponent makes of BMD, first, a more difficult design problem, since the offense constructs the worst possible barriers to successful defense; and second, not one problem but many problems that need to be sidestepped simultaneously in the design, since the designer cannot be certain which tactics the offense will use.

A third misapprehension concerns the prospect for a "technological breakthrough" that would dispel all difficulties. Such breakthroughs are not impossible, but their mere possibility does not help in judging the prospects for the perfect defense. For one thing, an isolated technological breakthrough creating a new defensive component would not necessarily alleviate the system issues—vulnerability, dependability, susceptibility to countermeasures, cost—that determine overall effectiveness. Second, one can just as easily imagine offensive "break throughs," sometimes involving the same technologies. Thus the x-ray laser, if it matures, might turn out to have been

'Defense Secretary Caspar Weinberger has w ritten *(Air Force Magazine, Nov. 1983):*

> **The nay-sayers have already proclaimed that we will never have such technology, or that we should never try to acquire it Their arguments are hardly new In 1945 President Truman's Chief of Staff, Adm William Leahy, said of the atomic bomb "Thatrs the biggest fool thing we've ever done. The bomb will never go off, and I speak as an expert in explosives. " In 1946 Dr. Vannevar Bush, Director of the Office of Scientific Research and Development said of Intercontinental ballistic missiles, "1 say technically I don't think anybody in the world knows how to do such a thing, and I *feel* confident it will not be done for a long time to come " These critics were proved wrong; what is more, they were proved wrong quickly**

better termed a breakthrough in strategic offense than a breakthrough in strategic defense.

A fourth misapprehension concerns the confidence with which predictions could be made about the performance of a complex system once in place. The "performance" of a system, as quoted in analyses, is the most likely outcome of an engagement of offense versus defense. Other outcomes, though less likely, might still be possible. Computing the relative likelihoods of all possible outcomes would be difficult even if one could quantify all technical uncertainties and statistical variances. Still, there would remain a residue of uncertainty about the performance of a system that had never been tested once in realistic wartime conditions, much less in a statistically significant ensemble of all-out nuclear wars. The defense would also have no chance to learn and adapt. In World War II, by contrast, air defense crews learned in raid after raid to inflict losses of several percent in attacking bombers. The only reason these modest losses assumed strategic significance was that they accumulated over many raids. Of course, the same uncertainties plague the offense as plague the defense. In general, the offense would tend to overestimate the defense's capability. This natural tendency toward "offense conservatism" is probably vitally important to the psychological and deterrent value of BMD as it is applied to less-than-perfect goals. For the perfect defense goal (as defined above), however, it would seem that the uncertainty weighs heaviest on the defense. To the reckless, non-conservative defense, a wrong estimate of defense performance spells the difference between safety and socially mortal damage (or between deterrence and war). The reckless offense, on the other hand, is presumed desperate enough to try to inflict such damage on its enemy and willing to accept the consequences: it stands to lose little if its estimates are wrong and the defense does work perfectly after all.

With these misapprehensions out of the way, and recognizing clearly that there can be no question of "proof," it would seem that four major factors conspire to make extremely remote the prospect that directed-energy BMD (in concert with other layers if necessary) will succeed in reducing the vulnerability of U.S. population and society to the neighborhood of 100 megatons or less.

1. **Near-perfect defense of society is much harder and more expensive than partial defense of military targets.** That is, the marginal cost exchange is much higher for near-perfect defense than for partial defense (see also Fig. 5.2). There are two reasons behind this well-known statement.

The first reason is illustrated schematically in Figure 8.2. **In going from partial silo defense to perfect city defense, the BMD loses the leverage of preferential defense. Additionally, the offense gains the leverage of preferential offense against the terminal and midcourse layers with their limited geographic coverage, although not against the boost-phase layer. In Figure 8.2(a), the defense aims to save only 10 percent of the ICBM** force, or one silo. Assuming perfect interceptors and adopting the tactic of adaptive preferential defense (using all its interceptors to save just one silo chosen randomly from the ten at the moment of attack), the defense concludes it needs to prepare to make one only intercept to counter the offense's 10 RVs. **In Figure 8.2(b), the offense can focus all 10 of its** RVs on any one of ten cities. The defense must prepare to make 10 intercepts for each city, buying a total of 100 interceptors, if it wants to try to save all the cities. If the Soviets double their **RV arsenal, the United States must** buy just one interceptor to satisfy the defense goal of Figure 8.2(a), but the United States must buy 100 **interceptors to satisfy the defense goal of Figure** 8.2(b). The cost exchange ratio is thus 100 times worse for the city defense, even though it uses the same technology **as the silo defense.**

The second reason why a near-perfect defensive goal shifts the cost burden in favor of the offense is that the offense can turn all its resources to improving or replacing just a portion of its ICBMs to sidestep the defense. The Soviet Union could therefore harden just 1 percent of its boosters, perhaps concealing exactly which ones were hardened. Moreover, it could deploy a few fast-burn boosters immune to x-ray lasers and neutral particle beams; build a few different ASAT de-

Figure 8.2

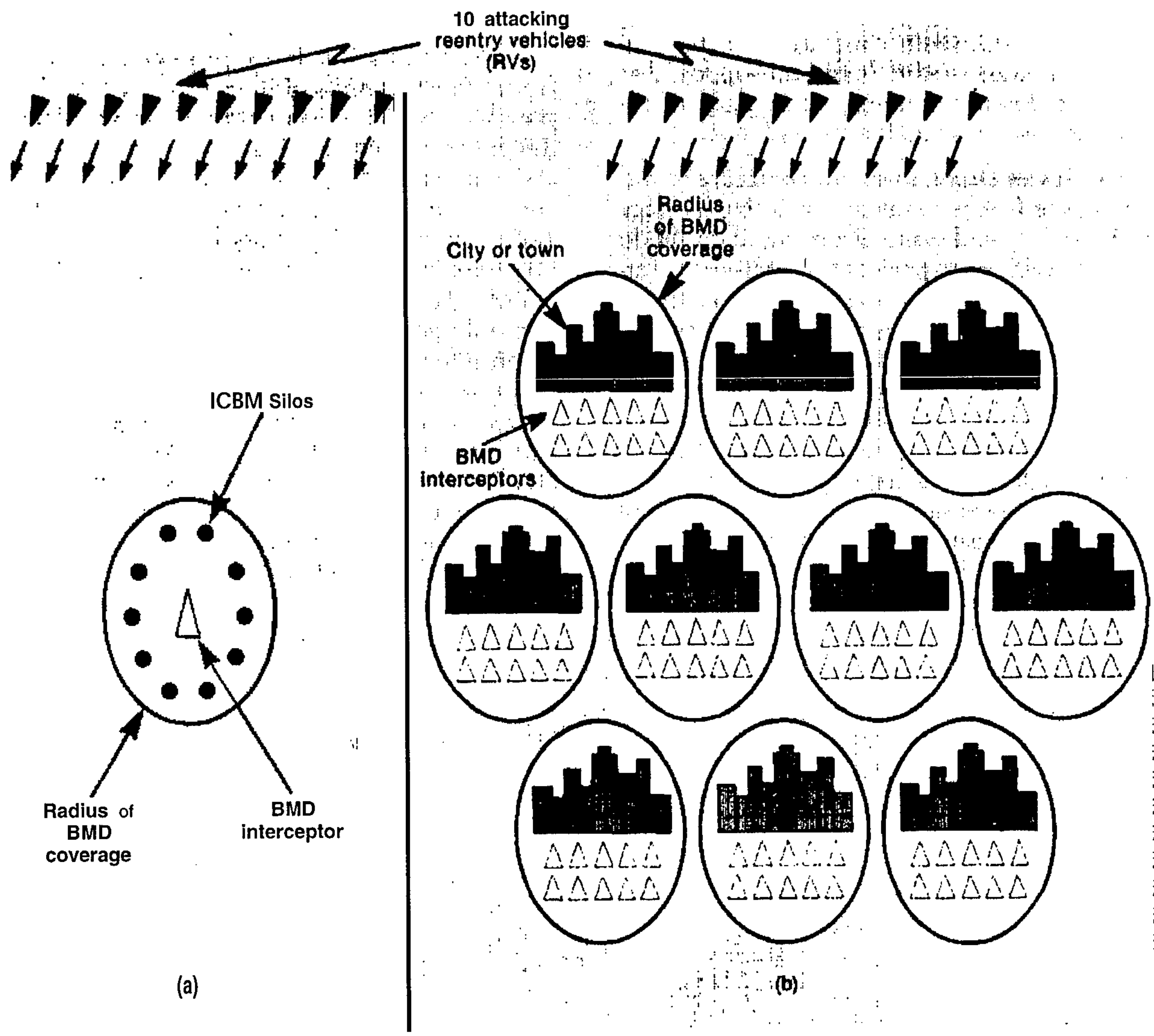


Figure 8.2. The cost to a U.S. reentry BMD to compete with increases in the size of the Soviet arsenal (the "marginal cost exchange") is much greater for near-perfect city defense (b) than for partial silo defense **(a).** In going from (a) to (b), the **U.S. loses** the leverage of preferential defense and the Soviet Union gains the leverage of preferential offense.

vices; and so on. More costly countermeasures are available to the offense if the countermeasures need only be implemented on a small scale rather than throughout the ICBM force. The offense can "experiment" with a number of different tactics with different portions of its force. The defense's costs also grow much larger if it must plan to face a ***variety*** of offensive countermeasures. In short, the defense must be able to stop all kinds of attack, but the offense only has to find one way to get-through.

2. **For every defense concept proposed or** imagined, **including all of the so-called "Star wars" concepts, a countermeasure has already been identified.** These countermeasures were enumerated in Section 5 and will not be repeated here. Three further generalizations about these countermeasures reinforce a poor prognosis for cost-effective near-perfect defense: 1) In general, the countermeasures could be implemented with today's technology, whereas the defense itself could not; 2) In general, the costs of the coun-

termeasures can be estimated and shown to be relatively low, whereas the costs of the defense are unknown but seem likely to be high; 3) In general, the future technologies presupposed as part of the defense concept would also be potent weapons for attacking the defense.

3. **The Soviet Union does not configure its nuclear missile forces today to maximize damage to U.S. society and population, but it could do so if faced with near-perfect U.S. defenses. Targeting plans could** focus exclusively on damaging cities. High missile accuracy would be unnecessary, **lowering offense costs. Nuclear weapons** could be designed to maximize harmful fallout. ICBM survivability measures–silos, racetracks, densepacks, etc.—would be unnecessary to a side striking first or possessing its own defense effective at saving many missiles (but not ***all*** cities); thus basing costs could be diverted to the city-kill goal, Presumably the Soviet Union would take these and any other measures necessary to prevent itself from being effectively disarmed by a U.S. defense, since otherwise it would be at its enemy's mercy.

4. **BMD by itself will not protect U.S. society from other methods of delivering nuclear weapons to U.S. soil or from other weapons of mass destruction.** Bombers and cruise missiles (and to a significant extent SLBMs and IRBMs) present very different defensive problems than ICBMs. Today the technical problems of air defense are no better resolved than the technical problems of BMD. Novel future offensive delivery vehicles can only be conjectured along with the future defense technologies discussed in this Paper. A desperate Soviet Union could introduce nuclear weapons into the United States on commercial airliners, ships, packing crates, diplomatic pouch, etc. Other methods of mass destruction or terrorism would be feasible for the U. S. S. R., including sabotage of dams or nuclear power plants, bacteriological attack, contaminating water, producing tidal waves with near-coastal underwater detonations, and so on.

Section 9

DEFENSIVE GOALS II: LESS-THAN-PERFECT DEFENSE

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A host of less grandiose goals than perfect or near-perfect defense assume importance i n certain theories about the workings of nuclear deterrence and the requirements of U.S. security. Thoughtful observers debate not just the feasibility of achieving these goals but the validity and importance of the goals as well. The urgency one attaches to these goals determines the costs, risks, and harmful side effects one is willing to incur to fulfill them. Assessing the wisdom of less-than-perfect defense thus involves a complex and subjective balancing of goals and risks, in which purely technical issues sometimes take a back seat. In discussion of perfect defense, by contrast, technical assessment is paramount. This section therefore calls up many issues of nuclear policy not subsumed under the title of this Background Paper, and no pretense is made hereto complete treatment.[1]

Though various strategic goals for BMD can be distinguished in principle, in practice it might not be clear or agreed among all parties in the United States what the purpose of a proposed deployment actually was. Interpretations by the Soviet Union and other foreign nations of U.S. goals might be quite different yet.

Those familiar with BMD design and assessment will recognize that stating a general strategic goal is not enough: the ***technical*** specifications are essential. For instance, it makes an enormous difference in silo defense whether the defense seeks to charge the offense a price of five RVs (or half a booster) or 10 RVs (one booster) per silo.

For goals requiring very modest performance, terminal and midcourse defenses might suffice. Since no one knows whether boost phase defenses, when better defined, will surpass or even equal traditional defenses in terms of leakage and cost exchange, there is no point i n turning to exotic technologies to satisfy modest goals. Virtually all observers agree, on the other hand, that terminal and midcourse systems are unequal to the more demanding goals; for these goals one is forced to direct one's hopes to the promise of future technologies.

This section sketches various goals for less-than-perfect defenses and the strategic thinking that attaches importance to them. **It** then points out a number of side effects against which fulfillment of these goals needs to be balanced. This short section is no substitute for a comprehensive assessment 01 the pros and cons of BMD.

[1] For a more complete treatment of the entire subject of BMD, see Ashton B. Carter and David N. Schwartz, cd., *Ballistic Missile Defense* (The Brookings Institution, 1984).

9.1 GOALS FOR LESS-THAN-PERFECT DEFENSE

1. Strengthen deterrence by preventing preemptive destruction of retaliatory forces. It is widely recognized that the Soviet Union will soon have, if it does not already, the combination of yields, numbers, and accuracy in its ICBM **forces to** destroy most U.S. Minuteman ICBMs **in their** silos. **It** is also widely agreed that vulnerable nuclear forces create unwanted temptations for both sides to strike first if war seems likely. The long and anguished search for survivable basing modes for the U.S. MX (Peacekeeper) ICBM has to date turned up no clear favorites when survivability is balanced against cost, technical risk, strategic effects, and environmental impacts.[2] **BMD would substitute** for or complement these other basing modes. By shooting down a fraction of the opponent's missiles, **BMD would** in effect "de-MIRV" ICBM **forces.**

Of course, turning to BMD to ease ICBM vulnerability is not without problems. One problem is the prospect of a compensating Soviet BMD.

[2] *MX Missile Basing*, Office of Technology Assessment, U.S. Congress, September 1981.

MX is presumably being bought and made **survivable** in the first place so that the U.S. can absorb a Soviet strike and retaliate with its ICBMs (in addition to its bombers and submarines) against Soviet targets. But modification or termination of the ABM Treaty to permit a U.S. defense would permit a Soviet defense as well. The surviving U.S. ICBMs guaranteed by the U.S. BMD might still not result in retaliatory damage to Soviet targets if these targets are defended by Soviet BMD. The U.S. BMD deployment, all bought and paid for, might therefore have been cancel led out by a Soviet counter-deployment,

Other elements of the U.S. retaliatory force comprise command and control links, bomber alert bases, and in-port submarines. Bomber bases, sub ports, and fixed command and control facilities are the worst type of target base for BMD to try to defend–a small number of high-value, soft, and interdependent targets. The important remaining category of mobile command and control facilities, on the other hand, does not easily lend itself to active defense with BMD.

2. **Strengthen deterrence by preventing the use of nuclear weapons as decisive military tools for high-confidence "limited" strikes on conventional forces. This goal is associated with so-called "warfighting" strategies for nuclear weapons. According to analysts who hold this view, today's "offense dominated" world creates dangerous temptations to resort to nuclear weapons to accomplish militarily well-defined objectives. One can imagine warheads simply being lobbed unopposed into another country in any number or combination. Though surely the effects of these "limited" attacks on nearby communities would not be so well-defined, the effect on the opposing military machine might be truly dramatic, even decisive. This use of nuclear weapons in wartime is possible with today's unopposed offenses with considerable confidence and might therefore be tempting to the combatants. Such temptations threaten nuclear deterrence and should be eliminated. The goal of a comprehensive defense would be to make such limited attacks infeasible, or at least to complicate the offense's estimations of success to such a degree that it would not attempt an "experiment."[3] Analysts who favor this approach usually maintain that Soviet military doctrine inclines the Soviets towards a view of nuclear weapons as military tools to a far greater degree than is common in U.S. thinking. d**

To take an explicit example (in this case of Soviet failure to deter the U. S.) of a "war fighting" scenario (chosen randomly from a great many possibilities), suppose NATO were at war with the Warsaw Pact, and the Soviets were resupplying their ground offensive through just 10 or so rail trunks from the Soviet Union through eastern Europe. Just 10 well-placed nuclear weapons (according to a hypothetical analyst considering this type of scenario) would cut off a large fraction of supplies coming to the front, slowing the Pact offensive and giving NATO vitally needed time to marshall its defenses. Wouldn't the United States be sorely tempted to use just a few ICBMs for this decisive intervention in the course of the war?

Analysts who recommend attention to warfighting scenarios and doctrines are surely aware of the profound difference between conventional and nuclear weapons, but they maintain that the threat of punishment through retaliation upon cities is not an effective deterrent in such scenarios. Wouldn't it be preferable if these scenarios were simply closed off by defensive technology?

Critics of this BMD goal object both to the warfighters' emphasis upon the risk of this type of scenario and to the assumption that defense would materially diminish that risk. In their view, myriad detailed chinks in the armor of deterrence can always be found, with or without defense, and worrying about them represents a loss of

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[3]Presidential Science Adviser George A. Keyworth, II has stated (interview with *US. News and World Report*, April 11, 1983, p. 24):

> "The objective is to have a system that would **convince an adversary that an offensive attack Will not be successful. It has to be a very effective system, but it would not have to be perfect to convince a potential adversary that his attack would fail**"

Dr. Robert Cooper, director of the Defense Advanced Research Projects Agency has also stated this view (The New *York Times, Nov. 5*, 1983, p. 32): "Even if only 50 percent of all incoming missiles were stopped, the Soviets could then have no confidence in the success of a first strike, and war would be more remote. "

[4]*Ballistic Missile Defense*, op. cit., Chapter 5.

perspective on the basic difference between nuclear and conventional instruments of war. Besides, they say, suppose the effect of the Soviet BMD is to force the United States to attack each rail line with ten weapons instead of one to assure penetration: is there truly a psychological divide between using 10 and 100 nuclear weapons, once the divide between O and 10 has been crossed? Third, would NATO not be adequately deterred by the prospect of Soviet retaliation with 10 of its nuclear weapons against 10 vital NATO targets? Last, suppose NATO used 10 cruise missiles, against which the BMD was powerless, instead of 10 ICBM RVs?

The persuasiveness of this second goal for less-than-perfect BMDs therefore depends on one's views of the roles and risks of nuclear weapons—views that are fundamental and deeply held. This goal is therefore one of the most controversial of all.

3. **Save lives.**[5] Another goal **for BMD is purely humanitarian and seeks no military or strategic advantage. If the defense did not interfere too much with Soviet military targeting objectives (enough for the Soviets to try to overcome it), and assuming the Soviets have no explicit aim to inflict human casualties, the United States could expect some reduction** in fatalities **in a nuclear war even from a modest defense.** This reduction would necessarily be limited, since Soviet military objectives include destruction of many targets collocated with population. BMD and civil defense measures would be mutually reinforcing.

Analogous discussion of civil defense has always revealed an inherent tension between the humanitarian objective of defense and a related strategic objective. The strategic objective seeks to reduce fatalities and damage in order to enhance U.S. "flexibility" in a crisis, to allow the United States to "coerce" the U.S.S.R. (or avoid coercion) from a position of reduced vulnerability, or to enhance U.S. ability to persist in its war effort despite receiving a **Soviet nuclear strike. The supposed result of the BMD deployment is to allow the U.S. President, in dealing with the Soviet leadership in time of crisis, to be more willing or appear to be more willing to resort to nuclear war because the consequences to the United States are presumed smaller.**

The coexistence of the humanitarian and strategic objectives for the analogous case of civil defense is apparent in the literature on civil defense. The Defense Department[6] has argued that the United States should have the same crisis relocation options as the U.S.S.R. for two reasons, one strategic and one humanitarian: 1) "to be able to respond in kind if the Soviet Union attempts to intimidate us in time of crisis by evacuating the population from its cities"; and 2) "to reduce fatalities if an attack on our cities appears imminent." Prominent scientists arguing for civil defense have also maintained that, "A nation's civil defense preparedness may determine the balance of power in some future nuclear crisis. . . . In our opinion, we must strive for an approximately equal casualty rate".[7] More recently, the High Frontier Study urging strengthened U.S. strategic defenses stated: "The protection of our citizens must be prime, but civil defense . . . would reduce the possibility that the United States could be **coerced** in a time of crisis". a

In practice, therefore, the humanitarian and strategic objectives are likely to be difficult to disentangle. Unlike the humanitarian objective, the strategic objective might stimulate a Soviet effort to put the same number of American lives at risk regardless of the defense. In this way, the Soviet Union could retain the strategic advantage that, by hypothesis, the BMD deprives them of. The issue then becomes the usual one of the cost-exchange ratio measuring the price to the Soviet Union of retaining its "advantage" relative to the price of the U.S. defense.

The Defense Department has stated that saving lives in time of war is not the purpose of President Reagan's BMD initiative.[9]

[5]This discussion borrows from the author's previous work in *Ballistic Missile Defense*, op. cit., Chapter 4.

[6]*Annual Defense Department Report, FY 1976*, p. 11-24.

[7]Arthur A. Broyles and Eugene P. Wigner, "Civil Defense in Limited War," *Physics Today*, vol 29 (April 1976), pp. 45-46,

[8]Daniel O. Graham, *The Non-Nuclear Defense of Cities: The High Frontier Space-Based Defense Against ICBM Attack* (Abt Books, 1983), p. 122.

[9]See footnote 8 2,

4. Shape the course of the arms competition and arms control.[10] One version of this goal sees the Soviet tendency to upgrade and proliferate existing ICBM forces as the principal impediment to arms control. By introducing BMD (or even discussing it), according to this view, the United States makes the Soviets unsure about the next step in the arms competition and thus undercuts the momentum of Soviet strategic programs, especially ICBM modernization. Though fast-burning Midgetman boosters might defeat boost-phase defenses, this argument goes, the slow-burning SS-18s and SS-19s will not. BMD might not be able to make all nuclear weapons impotent and obsolete, but it can make large Soviet ICBMs impotent and obsolete–something the U.S. has been trying to do for a decade. Perhaps efficient defenses will "force" the Soviets to emphasize submarines, bombers, and cruise missiles in their strategic arsenal to the same degree the United States does. (One problem with this line of argument is that by the time the defense is in place, present-generation Soviet ICBMs might already be replaced.)

Another line of argument holds that a major BMD initiative strengthens the U.S. negotiating position at START. An aggressive BMD program demonstrates U.S. technological prowess and hints at what the Soviets could face if this prowess were unleashed. It would seem that new BMD initiatives might not coexist easily with the reductions in offensive arsenals proposed by the United States in START, however. Since U.S. BMD is equivalent to attrition of the Soviet ICBM arsenal, any anxieties the Soviets feel at reducing the size of their missile inventories would, logically at least, be enhanced by a simultaneous U.S. BMD buildup. Politically, it would seem unlikely, though certainly not impossible, that a climate favorable to far-reaching offensive arms control would also foster an amicable dismantling of the ABM Treaty.

5. Respond to Soviet BMD efforts. Many analysts view with alarm Soviet strategic defense activities, including upgrading of the Moscow ABM, development of a transportable terminal BMD system, construction of a radar in apparent violation of the ABM Treaty, development of defenses against tactical ballistic missiles, incorporation of limited BMD capability in air defenses, and continued attention to other damage-limiting methods (civil defense, air defense, antisubmarine warfare, and countersilo ICBMs). A strong U.S. BMD research and development program might deter the Soviets from breaking out of the ABM Treaty and from continued encroachments on the Treaty's provisions. It is frequently noted that aggressive U.S. research into penetration aids and other methods for countering defenses might be an even more effective way to demonstrate to the Soviets that they would be ill-advised to overturn the ABM Treaty's "freeze" on missile defenses.

6. Protect against accidental missile launches and attack from other nuclear powers. These goals have been put forward several times in the past, most notably in the late 1960's when the Johnson Administration proposed the Sentinel ABM system to counter Chinese ICBMs, believed at that time to be fast-emerging. Neither goal figures prominently in today's discussion of BMD in the United States, though defense against Chinese, British, and French missiles could well loom larger in Soviet thinking. Emerging nuclear powers or terrorists would be unlikely to use ICBMs to deliver their small nuclear arsenals to the United States. BMD is therefore of little importance in staving off the threat to U.S. security posed by nuclear proliferation.

[10] Presidential science adviser George A. Keyworth, speech before the Washington chapter of the Armed Forces Communications and Electronics Association, as reported in *Defense Week* (Oct. 17, 1983):

> "Although the strategic defense program's goal would still be eventual deployment of a working system, we shouldn't overlook its potential beneficial impact on arms reduction as its progresses."

Richard DeLauer, Undersecretary of Defense for Research and Engineering, has said that an arms control agreement is needed to prevent the Soviets from overcoming a defensive system: "With unconstrained proliferation [of Soviet missiles], no defensive system will work." (Interview with *The New York Times*, May 18, 1983).

9.2 SIDE EFFECTS OF BMD DEPLOYMENT

The inevitable side effects of a major strategic initiative such as BMD might turn out to match, both in magnitude and in duration, the beneficial effects of satisfying the goal emphasized by the system's purveyors. The public and policy makers would therefore need to assess the net, long-term effect of adding BMD to the strategic equation, and not just the achievement of a certain discrete goal as if by surgical intervention. This section reviews the well-known list of BMD side effects. Many of these effects are detrimental to U.S. security and would need to be balanced against the benefits of fulfilling the modest goals of less-than-perfect defense. In making this assessment, it is impossible to ignore the many unknowns and uncertainties that make it impossible to compare today's world without BMD to a future world with BMD.

1. **First strike versus ragged retaliation. It is** frequently noted **that BMD ends up being a better investment** for the side that strikes first than for the side that retaliates. Weapon systems that create relative advantages to striking first in a crisis (rather than risking being struck while seeking a peaceful resolution) are defined to be "destabilizing." The side striking first uses its full arsenal in an organized penetration of the other side's de**fense; the retaliating side can only use its surviving arsenal in a possibly disorganized "ragged retaliation" against a forewarned and fully** prepared defense.

Mitigating factors could in certain circumstances soften this classical statement of the destabilizing effect of BMD. First, truly effective defenses might prevent the first striker from destroying a substantial fraction of the other side's retaliatory forces. Second, with proper planning (involving post-attack retargeting and coordinated timing), the retaliating forces might still be able to mount a tailored, efficient strike. Third, there will seemingly **always be a *relative* advantage to being** the side that strikes first in a nuclear war, with BMD or without BMD; but this calculus of relative advantage is far from being the only factor in deterrence. Other stabilizing factors might be strengthened by BMD, offsetting this destabilizing factor. Thus BMD might also ***discourage*** temptations to strike first, by threatening to disrupt the attack.

2. **Soviet BMD. A U.S. BMD deployment would seem very likely to stimulate a Soviet deployment. Even** if the Soviets saw no compelling military rationale for following suit, political appearances could prove decisive. A Soviet BMD counter-deployment would obviously blunt U.S. offensive striking power, which the U.S. has been spending a great deal to build up. If the U.S. deployment sought to protect its ICBMs from preemptive destruction in their silos (Goal 1 above), the Soviet BMD might nonetheless nullify the U.S. ICBMs–this time in flight to their targets. Soviet BMD would also introduce a threat to U.S. SLBMs, which are today thought to be virtually immune to Soviet disruption and to be significantly advanced relative to their Soviet counterparts. If the U.S. deployment sought to prevent "limited" strikes by the Soviets Union (Goal 2), the Soviet BMD might in turn preclude a U.S. option to use nuclear weapons selectively and flexibly in support of its NATO allies–an option sometimes seen as central to NATO strategy. Clearly the actual effect of the Soviet BMD counterdeployment would depend upon its technical characteristics and the targets it defended.

3. **Demise of the ABM Treaty. An arms control treaty obviously cannot serve as its own justification, and presumably virtually everyone would agree to the abandonment of the ABM Treaty the moment it ceased genuinely to serve the national security. In addition to its concrete provisions limiting BMD deployment, however, the ABM Treaty has unavoidably assumed a symbolic political meaning in the United States and,** in different forms perhaps, in Europe and the U.S.S.R. The Treaty stands for a decade of arms control and attempts at superpower understanding about nuclear weapons. As a practical matter, it is impossible to overturn the Treaty's technical provisions without calling into question U.S. commitment to the whole fabric of the SALT/START process. This side effect would have to be weighed against the purely military and strategic

benefit (if there were, in fact, a net long-term benefit) of a U.S. BMD deployment.

4. Allied and Chinese missile forces. The nuclear missile forces of Britain, France and China are obviously a greater threat to the Soviet Union than to the U.S. Most analysts agree that the existence of these forces enhances U.S. security. But a major BMD initiative sparking widespread Soviet defense would in effect disarm our allies (to a degree depending on the nature of the Soviet deployment).

5. **Accompanying strategic programs. A** number of new weapon systems and strategic **programs would be natural, though perhaps not necessary, accompaniments to BMD. On the offensive side, the U.S. would need to develop and deploy** penetration aids against the Soviet BMD and improve its bomber and cruise missile forces to reflect added reliance on non-missile delivery vehicles. on the defensive side, the overall category of "strategic defense" comprises, in addition to BMD: nationwide air defenses against Soviet bombers and cruise missiles, defensive coverage against SLBMs, civil defense shelters and evacuation plans, and passive "hardening" of military installations and industrial facilities.

6. **Opportunity Costs.** The initial investment in BMD deployment, the inevitable follow-ens, and any accompanying strategic programs would make a substantial, permanent demand on the defense budget, competing with other nuclear **forces and with conventional** forces, not to mention with nonmilitary expenditures.

In a more fundamental sense, the transition from a world with a near-total ban on BMD to a world with BMD deployments is probably an irreversible change. Reimposing a defensive "freeze" after a period of unrestrained deployment, much less dismantling defenses and returning to zero, would involve all of the problems that attend upon arms control reductions at START today. Extra caution seems warranted where strategic actions cannot easily be reversed or recalled: the opportunity for a comprehensive ban on missile defense might not arise again.

7. **Bean counting.** Strategists, politicians, and diplomats place considerable emphasis on quantitative measures of the nuclear balance and on "proofs" that "parity" exists. Arms control negotiations also reduce themselves quickly to counting rules. It is unclear whether or how BMD should affect such "bean counting. " For each U.S. battle station added to a defensive constellation, are the Soviets to be credited with fewer ICBMs, since the U.S. defense represents potential attrition of the Soviet force? How many Soviet interceptor missiles equals one U.S. laser? Whose estimate of the BMD's likely wartime performance–the defense's or the offense's--governs these counting rules? Experience indicates that these types of questions, however far-fetched and even preposterous they appear in prospect, in the end assume considerable perceived importance.

8. **Asymmetries.** The Soviet BMD deployment that could well follow **U.S.** deployment might not share the same defensive goal or the same technology, stimulating the usual anxieties about unequal intentions and capabilities. Defensive systems are also complex, leading different analysts to widely different conclusions about the likely wartime performance of the BMD systems on both sides. Moreoever the owner of the BMD, aware of all the system's hidden flaws, might credit it with little capability, whereas the offense planner will tend to give it the benefit of the doubt. Though some hypothetical future world with mutual BMD deployments might therefore appeal to one analyst or nation, another could easily have a completely different view of the technical and strategic "facts."

Section 10

PRINCIPAL JUDGMENTS AND OBSERVATIONS

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1. The prospect that emerging "Star Wars" technologies, when further developed, will provide a perfect or near-perfect defense system, literally removing from the hands of the Soviet Union the ability to do socially mortal damage to the United States with nuclear weapons, is so remote that it should not serve as the basis of public expectation or national policy about ballistic missile defense (BMD). This judgment appears to be the consensus among informed members of the defense technical community.

Technical prognosis for such a perfect or near-perfect defense is extremely pessimistic because of the concentration and fragility of society; because all concepts identified as candidates for a future defense of population are known to be susceptible to countermeasures that would permit the Soviet Union to retain a degree of penetration with their future missile arsenal despite costly attempts to improve the U.S. defense; because the Soviet Union would almost certainly make such a determined effort to avoid being disarmed by a U.S. defense; and because missile defense does not address other methods for delivering nuclear weapons to the United States.

Mutual assured destruction (MAD), if this term is applied to a state of technological existence rather than to a chosen national policy, is likely to persist for the foreseeable future.

2. **The wisdom of deploying less-than-perfect ballistic missile defenses remains controversial.** Less-than-perfect defenses would still allow the Soviet Union to destroy U.S. society in a massive attack but might call into question the effectiveness of smaller, specialized nuclear strikes.

Certain theories about nuclear war maintain that such defenses could lessen the chances of nuclear war and enhance U.S. security by protecting U.S. retaliatory forces; by interdicting "limited" nuclear strikes; by further confusing Soviet predictions of the outcome of a strike; by driving Soviet missile deployments in directions favored by the United States; by lessening the consequences of nuclear attack; and/or by fulfilling still other strategic goals.

Critics dispute the validity of some of these goals; dispute that technology can fulfill the truly useful goals; and/or argue that the many harmful side effects of introducing BMD to the strategic equation and altering the Anti-Ballistic Missile (ABM) Treaty regime are not worth satisfying these goals.

To address the wisdom of less-than-perfect defense, the public and policy makers would need a precise statement of the strategic goal of the deployment, an assessment of whether technology could satisfy that goal, and an analysis balancing fulfillment of the goal against the side effects and uncertainties of introducing a new ingredient into the strategic nuclear arena.

3. **The strategic goal of President Reagan's Strategic Defense Initiative calling for emphasized BMD research—perfect, near-perfect, or less-than-perfect defense against ballistic missiles—remains unclear. No** explicit technical standards or criteria are therefore available against which to measure the technological prospects and progress of this initiative.

4. **In all cases, directed-energy weapons and other devices with the specifications needed for boost-phase intercept of ICBMs have not yet been built in the laboratory, much less in a form suitable for incorporation in a complete defense system.** These devices include chemical lasers, excimer and free electron lasers, x-ray lasers, particle beams, lightweight high-velocity kinetic energy weapons, and microwave generators, together with tracking, aiming, and pointing mechanisms, power sources, and other essential accompaniments.

It is unknown whether or when devices with the required specifications can be built,

5. **Moreover, making the technological devices perform to the needed specifications in a controlled situation is not the crux of the technical challenge facing designers of an effective ballistic missile defense. A distinct challenge is to fashion from these devices a reliable defensive architecture, taking into account vulnerability**

of the defense components, susceptibility to future Soviet countermeasures, and cost relative to those countermeasures.

New intercept mechanisms–directed energy weapons and the like—therefore do not by themselves necessarily herald dramatically new BMD capabilities.

6. **It is clear that potent directed-energy weapons will be developed for other military purposes, even if such weapons are never incorporated into effective BMDs.** Such weapons might have a **role** in nuclear offense as **well as defense,** in anti-satellite (ASAT) attack, in antiaircraft attack, and in other applications of concern to nuclear policy and arms control. Defense and arms control policy will thus need to face the advent of these new weapons, irrespective of their BMD dimension.

7. For modest defensive goals requiring less-than-perfect performance, traditional reentry phase defenses and/or more advanced midcourse defenses might suffice. Such defenses present less technical risk than systems that incorporate a boost-phase layer, and they could probably be deployed more quickly.

New ideas for improving such "old" BMD concepts have emerged in the atmosphere of technical optimism enjoyed by the boost-phase concepts.

8. **Deployment of missile defenses based on new technologies is forbidden by the Anti-Ballistic Missile (ABM) Treaty reached at SALT 1.** The Treaty permits only restricted deployment of traditional BMDs using fixed, ground-based radars and interceptor missiles. Research into new technologies, and in selected cases development and testing of defense systems based on these technologies, are allowed within the Treaty.

9. **There is a close connection, not explored in detail in this Background Paper, between advanced BMD concepts and future anti-satellite (ASAT) systems.** This connection springs from four observations: 1) ASAT attack on space-based weapons and sensors is probably the most attractive countermeasure to boost-phase BMD; 2) directed-energy weapons are more likely to succeed in the easier mission of **ASAT than in the more difficult mission of boost-phase BMD; 3) to a degree dependent on technical details, early stages of development of boost phase BMDs might be conducted in the guise** of ASAT development, stimulating anxieties about the health of the ABM Treaty regime; 4) to a degree dependent on technical details, concluding a treaty with the Soviet Union limiting ASAT development would impede BMD research at an earlier stage than would occur under the terms of the ABM Treaty alone.

APPENDIXES

APPENDIX A: THE CONCLUSION OF PRESIDENT REAGAN'S MARCH 23, 1983, SPEECH ON DEFENSE SPENDING AND DEFENSIVE TECHNOLOGY

Weekly Compilation of

Presidential Documents

Monday, March **28, 1983**
Volume 19—Number 12
Pages 423-466

No, thus far tonight I've shared with you my thoughts on the problems of national security we must face together. My predecessors in the Oval Office have appeared before you on other occasions to describe the threat posed by Soviet power and have proposed steps to address that threat. **But** since the advent of nuclear weapons, those steps have been increasingly directed toward deterrence of aggression through the promise of retaliation.

This approach to stability through offensive threat has worked. We and our allies have succeeded in preventing nuclear war for more than three decades. In recent months, however, my advisers, including in particular the Joint Chiefa of Staff, have underscored the necessity to break out of a future that relies solely on offensive retaliation for our security.

Over the course of these discussions, I've become more and more deeply convinced that the human spirit must be capable of rising above dealing with other nations and human beings by threatening their existence. Feeling this way, I believe we must thorough])' examine every opportunity for reducing tensions and for introducing greater stability into the strategic calculus on both sides.

One of the most important contributions we can make is, of course, to *lower* the level of all arms, and particularly nuclear arms. We're engaged right now in several negotiations with the Soviet Union to bring about a mutual reduction of weapons. I will report to you a week from tomorrow my thoughts on that score. But let me just say, I'm totally committed to this course.

If the Soviet Union will join with us in our effort to achieve major arms reduction, we will have succeeded in stabilizing the nuclear balance. Nevertheless, it will still be necessary to rely on the specter of retaliation, on mutual threat. And that's a sad commentary on the human condition. Wouldn't it be better to save lives than to avenge them? Are we not capable of demonstrating our peaceful intentions by applying all our abilities and our ingenuity to achieving a truly lasting stability? I think we are. Indeed, we must.

After careful consultation with my advisers, including the Joint Chiefs of Staff, I believe there is a way. Let me share with you a vision of the future which offers hope. It is that we embark on a program to counter the awesome Soviet missile threat with measures that are defensive. Let us turn to the very strengths in technology that spawned our great industrial base and that have given us the quality of life we enjoy today.

What if free people could live secure in the knowledge that their security did not rest upon the threat of instant U.S. retaliation to deter a Soviet attack, that we could intercept and destroy strategic ballistic missiles before they reached our own soil or that of our allies?

I know this is a formidable, technical task, one that may not be accomplished before the end of this century. Yet, current technology has attained a level of sophistication where it reasonable for us to begin this effort. It will take years, probably decades of effort on many fronts. There will be failures and setbacks, just as there will be successes and breakthroughs. And as we proceed, we must remain constant in preserving the nuclear deterrent and maintaining a solid capability for flexible response. **But isn't it worth every investment necessary to** free the world from the threat of nuclear war? **We know it is.**

In the meantime, we will continue to pursue real reductions in nuclear arms, negotiating from a position of strength that can be ensured only by modernizing our strategic forces. At the same time, we must take steps to reduce the risk of a conventional military conflict escalating to nuclear war by improving our non-nuclear capabilities.

America does possess-now-the technologies to attain very significant improvements in the effectiveness of our conventional, non-nuclear forces. Proceeding boldly with these new technologies, we can significantly **reduce any** incentive that the Soviet Union **may** have to threaten attack against the United States or its allies.

As we pursue our goal of defensive technologies, we recognize that our allies rely upon our strategic offensive power to deter attacks against them. Their vital interests and ours arc inextricably linked. Their safety and ours are one. And no change in technology can or will alter that reality. We must and shall continue to honor our commitments.

1 clearly recognize that defensive systems have limitations and raise certain problems and ambiguities. If paired with offensive systems, they can be viewed as fostering an agressive policy, and no one wants that But with these considerations firmly in mind. I call upon the scientific community in our country, those who gave us nuclear weapons, to turn their great talents now to the cause of mankind and world peace, to give us the means of rendering these nuclear weapons inopotent and obsolete.

Tonight, consistent with our obligations of the ABM treaty and recognizing the need for closer consultation with our allies, I'm taking an important first step. I am directing a comprehensive and intensive effort to define a long-term research and develop ment program to begin to achieve our ultimate goal of eliminating the threat posed by strategic nuclear missiles. This could pave the way for arms control **measures to eliminate the weapons themselves.** We seek **neither military superiority nor political advantage.** Our only purpose-one all people share—is to search for ways to reduce the danger of nuclear war.

My fellow Americans, tonight we're launching an effort which holds the promise of changing the course of human history. There will be risks, and results take time. **But I** believe we can do it. As we cross this threshold, I ask for your prayers and your support.

Thank you, good night, and Cod bless you.

Note: The President spoke at 8:02 p.m. from the Oval Office at the White *House. The address was broadcast* **live** *on notion* ***wide radio*** *and television.*

Following his remarks, the President met in the White House with o number of administration officials, ***including members*** *of the Cabinet, the White House staff, and the Joint Chiefs of Staff and former officials of past administrations to discuss the address.*

APPENDIX B: ABM TREATY AND RELATED DOCUMENTS

1980 **EDITION**

ARMS CONTROL AND DISARMAMENT AGREEMENTS

TEXTS **AND** HISTORIES
OF NEGOTIATIONS

UNITED STATES
ARMS CONTROL
AND
DISARMAMENT
AGENCY

WASHINGTON, D. C., 20451

Treaty Between the United States of America and the Union of Soviet Socialist Republics on the Limitation of Anti-Ballistic Missile Systems

Signed at Moscow May 26, 1972
Ratification advised by U.S. Senate August 3, 1972
Ratified by U.S. President September 30, 1972
Proclaimed by U.S. President October 3, 1972
Instruments of ratification exchanged October 3, 1972
Entered into force October 3, 1972

The United States of America and the Union of Soviet Socialist Republics, hereinafter referred to as the Parties,

Proceeding from the premise that nuclear war would have devastating consequences for all mankind,

Considering that effective measures to limit anti-balllstic missile systems would be a substantial factor in curbing the race in strategic offensive arms and would lead to a decrease in the risk of outbreak of war involving nuclear weapons,

Proceeding from the premise that the limitation of anti-ballistic missile systems, as well as certain agreed measures with respect to the lmitation of strategic offensive arms, would contribute to the creation of more favorable conditions for further negotiations on limiting strategic arms,

Mindful of their obligations under Article VI of the Treaty on the Non- Proliferation of Nuclear Weapons,

Declaring their intention to achieve at the earnest possible date the cessation of the nuclear arms race and to take effective measures toward reductions in strategic arms, nuclear disarmament, and general and complete disarmament,

Deskiring to contribute to the relaxation of International tension and the strengthening of trust between States,

Have agreed as follows

Article I

1 Each party undertakes to limit anti-ballistic missile (ABM) systems and to adopt other measures in accordance with the provisions of this Treaty.

2 Each Party undertakes not to deploy ABM systems for a defense of the territory of its country and not to provide a base for such a defense, and not to deploy ABM systems for defense of an individual region except as provided for in Article III of this Treat y

Article II

1 For the purpose of this Treaty an ABM system is a system to counter strategic ballistic missiles or their elements in flight trajectory, currently consisting of:

(a) ABM Interceptor missiles, which are Interceptor missiles constructed and deployed for an ABM role, or of a type tested in an ABM mode,

(b) ABM launchers, which are launchers constructed and deployed for launching ABM interceptor missiles; and

(c) ABM radars, which are radars constructed and deployed for an ABM role, or of a type tested in an ABM mode.

2. The ABM system components listed in paragraph 1 of this Article include those which are:

(a) operational;
(b) under construction;
(c) undergoing testing;
(d) undergoing overhaul, repair or conversion; or
(e) mothballed

Article III

Each Party undertakes not to deploy ABM systems or their components except that.

(a) within one ABM system deployment area having a radius of one hundred and fifty kilometers and centered on the Party's national capital, a Party may deploy (1) no more than one hundred ABM launchers and no more than one hundred ABM Interceptor missiles at launch sites, and (2) ABM radars within no more than six ABM radar complexes, the area of each complex being circular and having a diameter of no more than three kilometers; and

(b) within one ABM system deployment area having a radius of one hundred and fifty kilometers and containing ICBM silo launchers, a Party may deploy' (1) no more than one hundred ABM launchers and no more than one hundred ABM Interceptor missiles at launch sites, (2) two large phased-array ABM radars comparable in potential to corresponding ABM radars operational or under construction on the date of signature of the Treaty in an ABM system deployment area containing ICBM silo launchers, and (3) no more than eighteen ABM radars each having a potential less than the potential of the smaller of the above-mentioned two large phased-array ABM radars.

Article IV

The limitations provided for in Article III shall not apply to ABM systems or their components used for development or testing, and located within current or additionally agreed test ranges, Each Party may have no more than a total of fifteen ABM launchers at test ranges.

Article V

1 Each Party undertakes not to develop, test, or deploy ABM systems or components which are sea-based, air-based, space-based, or mobile land-based

2. Each Party undertakes not to develop, test, or deploy ABM launchers for launching more than one ABM interceptor missile at a time from each launcher, not to modify deployed launchers to provide them with such a capability, not to develop, test, or deploy automatic or semi-automatic or other similar systems for rapid reload of ABM launchers.

Article VI

To enhance assurance of the effectiveness of the limitations on ABM systems and their components provided by the Treaty, each Party undertakes

(a) not to give missiles, launchers, or radars, other than ABM interceptor missiles, ABM launchers, or ABM radars, capabilities to counter strategic ballistic missiles or their elements in flight trajectory, and not to test them in an ABM mode; and

(b) not to deploy in the future radars for early warning of strategic ballistic missile attack except at locations along the periphery of its national territory and oriented outward.

Article VII

Subject to the provisions of this Treaty, modernization and replacement of ABM systems or their components may be carried out.

Article VIII

ABM systems or their components in excess of the numbers or outside the areas specified in this Treaty, as well as ABM systems or their components prohibited by this Treaty, shall be destroyed or dismantled under agreed procedures within the shortest possible agreed period of time.

Article IX

To assure the viability and effectiveness of this Treaty, each Party undertakes not to transfer to other States, and not to deploy outside its national territory, ABM systems or their components limited by this Treaty.

Article X

Each Party undertakes not to assume any international obligations which would conflict with this Treaty.

Article XI

The Parties undertake to continue active negotiations for limitations on strategic offensive arms

Article XII

1. For the purpose of providing assurance of compliance with the provisions of this Treaty, each Party shall use national technical means of verification at its disposal in a manner consistent with generally recognized principles of international law.

2. Each Party undertakes not to interfere with the national technical means of verification of the other Party operating in accordance with paragraph 1 of this Article.

3. Each Party undertakes not to use deliberate concealment measures which impede verification by national technical means of compliance with the provisions of this Treaty. This obligation shall not require changes in current construction, assembly, conversion, or overhaul practices.

Article XIII

1. To promote the objectives and implementation of the provisions of this Treaty, the Parties shall establish promptly a Standing Consultative Commission, within the framework of which they will:

(a) consider questions concerning compliance with the obligations assumed and related situations which may be considered ambiguous;

(b) provide on a voluntary basis such information as either Party considers necessary to assure confidence in compliance with the obligations assumed,

(c) consider questions involving unintended Interference with national technical means of verification,

(d) consider possible changes in the strategic situation which have a bearing on the provisions of this Treaty;

(e) agree upon procedures and dates for destruction or dismantling of ABM systems or their components in cases provided for by the provisions of this Treaty;

(f) consider, as appropriate, possible proposals for further increasing the viability of this Treaty; including proposals for amendments in accordance with the provisions of this Treaty,

(g) consider, as appropriate, proposals for further measures aimed at limiting strategic arms.

2 The Parties through consultation shall establish, and may amend as appropriate, Regulations for the Standing Consultative Commission governing procedures, composition and other relevant matters.

Article XIV

1 Each Party may propose amendments to this Treaty Agreed amendments shall enter into force in accordance with the procedures governing the entry into force of this Treaty.

2 Five years after entry into force of this Treaty, and at five-year internals thereafter, the Parties shall together conduct a review of this Treaty.

Article XV

1 This Treaty shall be of unlimited duration.

2. Each Party shall, in exercising its national sovereignty, have the right to withdraw from this Treaty if it decides that extraordinary events related to the subject matter of this Treaty have jeopardized its supreme Interests. It shall give notice of its decision to the other Party six months prior to withdrawal from the Treaty. Such notice shall include a statement of the extraordinary events the notifying Party regards as having jeopardized its supreme Interests.

Article XVI

1 This Treaty shall be subject to ratification in accordance with the constitutional procedures of each Party, The Treaty shall enter into force on the day of the exchange of Instruments of ratification.

2. This Treaty shall be registered pursuant to Article 102 of the Charter of the United Nat lons.

DONE at Moscow on May 26, 1972, in two copies, each in the English and Russian languages, both texts being equally authentic.

FOR THE UNITED STATES OF AMERICA	FOR THE UNION OF SOVIET SOCIALIST REPUBLICS
President of the United States of America	*General Secretary of the Central Committee* of the CPSU

Agreed Statements, Common Understandings, and Unilateral Statements Regarding the Treaty Between the United States of America and the Union of Soviet Socialist Republics on the Limitation of Anti-Ballistic Missiles

1. Agreed Statements

The document set forth below was agreed upon and initialed by the Heads of the Delegations on May 26, 1972 (letter designations added);

AGREED STATEMENTS REGARDING THE TREATY BETWEEN THE UNITED STATES OF AMERICA AND THE UNION OF SOVIET SOCIALIST REPUBLICS ON THE LIMITATION OF ANTI-BALLISTIC MISSILE SYTEMS

[A]

The Parties understand that, in addition to the ABM radars which maybe deployed in accordance with subparagraph (a) of Article III of the Treaty, those non-phased-array ABM radars operational on the date of signature of the Treaty within the ABM system deployment area for defense of the national capital may be retained.

[B]

The Parties understand that the potential (the product of mean emitted power in watts and antenna area in square meters) of the smaller of the two large phased-array ABM radars referred to in subparagraph (b) of Article III of the Treaty is considered for purposes of the Treaty to be three million.

[C]

The Parties understand that the center of the ABM system deployment area centered on the national capital and the center of the ABM system deployment area containing ICBM silo launchers for each Party shall be separated by no less than thirteen hundred kilometers.

[D]

In order to insure fulfillment of the obligation not to deploy ABM systems and their components except as provided in Article III of the Treaty, the Parties agree that in the event ABM systems based on other physical principles and including components capable of substituting for ABM interceptor missiles, ABM launchers, or ABM radars are created in the future, specific limitations on such systems and their components would be subject to discussion in accordance with Article XIII and agreement in accordance with Article XIV of the Treaty.

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[E]

The Parties understand that Article V of the Treaty includes obligations not to develop, test or deploy ABM interceptor missiles for the delivery by each ABM interceptor missile of more than one independently guided warhead.

[F]

The Parties agree not to deploy phased-array radars having a potential (the product of mean emitted power in watts and antenna area in square meters) exceeding three million, except as provided for in Articles III, IV and VI of the Treaty, or except for the purposes of tracking objects in outer space or for use as national technical means of verification.

[G]

The Parties understand that Article IX of the Treaty includes the obligation of the US and the USSR not to provide to other States technical descriptions or blue prints specially worked out for the construction of ABM systems and their components limited by the Treaty.

2. Common Understandings

Common understanding of the Parties on the following matters was reached during the negotiations:

A. Location of ICBM Defenses

The U.S. Delegation made the following statement on May 26, 1972:

Article III of the ABM Treaty provides for each side one ABM system deployment area centered on its national capital and one ABM system deployment area containing ICBM silo launchers. The two sides have registered agreement on the following statement: "The Parties understand that the center of the ABM system deployment area centered on the national capital and the center of the ABM system deployment area containing ICBM silo launchers for each Party shall be separated by no less than thirteen hundred kilometers." in this connection, the U.S. side notes that its ABM system deployment area for defense of ICBM silo launchers, located west of the Mississippi River, will be centered in the Grand Forks ICBM silo launcher deployment area. (See Agreed Statement [C].)

B. ABM Test Ranges

The U.S. Delegation made the following statement on April 26, 1972:

Article IV of the ABM Treaty provides that "the limitations provided for in Article III shall not apply to ABM systems or their components used for development or testing, and located within current or additionally agreed test ranges. " We believe it would *be* useful to assure that there is no misunderstanding as to current ABM test ranges. it is our understanding that ABM test ranges encompass the area within which ABM components are located for test purposes. The current U.S. ABM test ranges are at White Sands, New Mexico, and at Kwajalein Atoll, and the current Soviet ABM test range is near Sary Shagan in Kazakhstan. We consider that non-phased array radars of types used for range safety or instrumentation purposes maybe located outside of ABM test ranges. We Interpret the reference in Article IV to "additionally agreed test

ranges" to mean that ABM components will not be located at any other test ranges without prior agreement between our Governments that there will be such additional ABM test ranges.

On May 5, 1972, the Soviet Delegation stated that there was a common understanding on what ABM test ranges were, that the use of the types of non-ABM radars for range safety or instrumentation was not limited under the Treaty, that the reference in Article IV to "additionally agreed" test ranges was sufficiently clear, and that national means permitted identifying current test ranges.

C Mobile ABM Systems

On January 29, 1972, the U.S. Delegation made the following statement:

Article V(I) of the Joint Draft Text of the ABM Treaty includes an undertaking not to develop, test, or deploy mobile land-based ABM systems and their components. On May 5, 1971, the U.S. side indicated that, in its view, a prohibition on deployment of mobile ABM systems and components would rule out the deployment of ABM launchers and radars which were not permanent fixed types. At that time, we asked for the Soviet view of this interpretation. Does the Soviet side agree with the U.S. side's interpretation put forward on May 5, 1971?

On April 13, 1972, the Soviet Delegation said there is a general common understanding on this matter.

D. Standing Consultative Commission

Ambassador Smith made the following statement on May 22, 1972

The United States proposes that the sides agree that, with regard to initial implementation of the ABM Treaty's Article XIII on the Standing Consultative Commission (SCC) and of the consultation Articles to the Interim Agreement on offensive arms and the Accidents Agreement, [1] agreement establishing the SCC will be worked out early in the follow-on SALT negotiations; until that is completed, the following arrangements will prevail: when SALT is in session, any consultation desired by either side under these Articles can be carried out by the two SALT Delegations, when SALT is not in session, *ad hoc* arrangements for any desired consultations under these Articles may be made through diplomatic channels.

Minister Semenov replied that, on an *ad referendum* basis, he could agree that the U.S. statement corresponded to the Soviet understanding

E. Standstill

On May 6, 1972, Minister Semenov made the following statement.

In an effort to accommodate the wishes of the U S side, the Soviet Delegation is prepared to proceed on the basis that the two sides will in fact observe the obligations of both the Interim Agreement and the ABM Treaty beginning from the date of signature of these two documents.

In reply, the U.S. Delegation made the following statement on May 20, 1972:

[1] See Article 7 of Agreement to Reduce the Risk of Outbreak of Nuclear War Between the United States of America and the Union of Soviet Socialist Republics, signed Sept. 30, 1971

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The U.S. agrees in principle with the Soviet statement made on May 6 concerning observance of Obligations beginning from date of signature but we would like to make clear our understanding that this means that, pending ratification and acceptance, neither side would take any action prohibited by the agreements after they had entered into force This understanding would continue to apply in the absence of notification by either signatory of its Intent Ion not to proceed with ratification or approval

The Soviet Delegation Indicated agreement with the U S. statement

3. Unilateral Statements

The following noteworthy unilateral statements were made during the negotiations by the United States Delegation

A. Withdrawal from the ABM Treaty

On May 9, 1972, Ambassador Smith made the following statement.

The U.S. Delegation has stressed the Importance the U. S. Government attaches to achieving agreement on more complete limitations 011 strategic offensive arms, following agreement on an ABM Treaty and on an Interim Agreement on certain measures with respect to the limitation of strategic offensive arms The U S Delegation believes that an objective of the follow-on negotiations should be to constrain and reduce on a long-term basis threats to the survivability of our respective strategic retaliatory forces The USSR Delegation has also Indicated that the objectives of SALT would remain unfulfilled without the achievement of an agreement providing for more complete limitations on strategic offensive arms. Both sides recognize that the initial agreements would be steps toward the achievement of more complete limitations on strategic arms. If an agreement providing for more complete strategic offensive arms limitations were not achieved within five years, U S supreme Interests could be jeopardized Should that occur, it would constitute a basis for withdrawal from the ABM Treaty The U.S. does not wish to see such a situation occur, nor do we believe that the USSR does It is because we wish to prevent such a situation that we emphasize the Importance the U.S. Government attaches to achievement of more complete limitations on strategic offensive arms The U.S. Executive will inform the Congress, in connection with Congressional consideration of the ABM Treaty and the Interim Agreement, of this statement of the U S position

B. Tested in ABM Mode

On April 7, 1972, the U.S. Delegation made the following statement.

Article II of the Joint Text Draft uses the term "tested in an ABM mode," in defining ABM components, and Article VI includes certain obligations concerning such testing. We believe that the sides should have a common understanding of this phrase. First, we would note that the testing provisions of the ABM Treaty are intended to apply to testing which occurs after the date of signature of the Treaty, and not to any testing which may have occurred in the past, Next, we would amplify the remarks we have made on this subject during the previous Helsinki phase by setting forth the objectives which govern the U.S. view on the subject, namely, while prohibiting testing of non-ABM components for ABM purposes. not to prevent testing of ABM components, and not to prevent testing of non-ABM components for

non-ABM purposes. To clarify our interpretation of "tested in an ABM mode, " we note that we would consider a launcher, missile or radar to be "tested in an ABM mode" if, for example, any of the following events occur: (1) a launcher is used to launch an ABM Interceptor missile, (2) an Interceptor missile is flight tested against a target vehicle which has a flight trajectory with characteristics of a strategic ballistic missile flight trajectory, or is flight tested in conjunction with the test of an ABM Interceptor missile or an ABM radar at the same test range, or is flight tested to an altitude inconsistent with Interception of targets against which air defenses are deployed, (3) a radar makes measurements on a cooperative target vehicle of the kind referred to in item (2) above during the reentry portion of its trajectory or makes measurements in conjunction with the test of an ABM interceptor missile or an ABM radar at the same test range. Radars used for purposes such as range safety or Instrumentation would be exempt from application of these criteria.

C. No-Transfer Article of ABM Treaty

On April 18, 1972, the U.S. Delegation made the following statement:

In regard to this Article [IX], I have a brief and I believe self-explanatory statement to make. The U.S. side wishes to make clear that the provisions of this Article do not set a precedent for whatever provision may be considered for a Treaty on Limiting Strategic Offensive Arms. The question of transfer of strategic offensive arms is a far more complex issue, which may require a different solution.

D. No Increase in Defense of Early Warning Radars

On July 28, 1970, the U.S. Delegation made the following statement:

Since Hen House radars [Soviet ballistic missile early warning radars] can detect and track ballistic missile warheads at great distances, they have a significant ABM potential. Accordingly, the U.S. would regard any increase in the defenses of such radars by surface-to-air missiles as inconsistent with an agreement.

APPENDIX C: OTHER APPLICATIONS OF DIRECTED ENERGY WEAPONS

This Background Paper treats only one–and probably one of the most difficult-military application of directed energy. Many other applications of widely varying plausibility vie for funding and attention. An assessment of all these **schemes** is well beyond the scope of this Paper, but the list below is provided for reference. Mention of a scheme does not imply that it has any technical or military promise; this question would have to be properly studied.

Anti-satellite (ASAT). Directed energy attack on satellites from space-, air-, or ground-based weapons is substantially easier than boost phase BMD. A satellite's orbit is completely predictable, making it in effect a fixed target. Long dwell times and low fluences suffice for ASAT attack on unshielded satellites. For instance, long illumination at just a few watts/cm^2 (several times **the sun's normal irradiance** in space) could upset the thermal control systems that allow spacecraft to endure the extremes of heat and cold in outer space. Substantial hardening of large and com**plex satellites (including sensors) to directed** energy weapons from all directions at all times is impractical. Unlike BMD, which must handle thousands of boosters in a few minutes, ASATs would have fewer targets and longer attack times. Last, BMDs must operate under the most hostile circumstances imaginable, whereas the superpowers might use ASATs in scenarios short of nuclear war.

This Background Paper has stressed (see Section 5.1) that maturation of the same technologies involved in boost phase BMD virtually assures potent ASATs. The so-called "Star Wars" systems could well be their own worst threats. Besides the intrinsic ease of ASAT over BMD, a Soviet defense suppression ASAT attack on U.S. defensive battle stations would have three key factors working in its favor: 1) The Soviets would pick the time and sequence of attack on the U.S. BMD system and launch of their ICBMs; 2) The Soviets need not destroy the entire defensive constellation, but only "punch a hole" for their ICBMs to pass through; 3) The attack would take place over Soviet territory.

Ground-based laser ASATs, presumably using excimer or free-electron lasers for best atmospheric propagation, would have the advantages of large size and power supplies. Airborne lasers could avoid some of the propagation disturbances introduced by denser air at low altitudes, but turbulence around the airplane skin could require adaptive beam compensation.

Space-based directed energy ASATs are the most interesting category of all, since they would be, in effect, long-range space mines, Rather than positioning itself next to its quarry like an ordinary space mine, a **laser** could be thousands of kilometers away and still be able to strike within milliseconds upon receipt of a radio signal from the gound.

Strategic offense. **If** they mature, the directed energy devices discussed for BMD might turn out to have been better termed "offensive breakthroughs" than "defensive breakthroughs." Consider, for example, a fleet of Soviet x-ray lasers launched simultaneously with (or minutes before) a Soviet first-stike ICBM attack. The pop-up x-ray lasers' job would be to intercept any U.S. ICBMs launched before arrival of Soviet silo-killing **RVs. The Soviet x-ray lasers would therefore** deprive the U.S. of its option for launch under attack. Microwave generators might be used for EMP-like attack on the U.S. command and control system. Another example of offensive use of beam weapons would be Soviet ASAT attack on U.S. warning, communications, nuclear detonation detection, or navigation satellites important to the U.S. retaliatory capability. Yet another example would of course be suppression of any U.S. BMD that used space-based weapons or sensors.

Bus intercept. This Background Paper has focused on intercept of ICBMs before booster burnout. Intercept of the bus or post boost vehicle poses a rather different challenge. Post-boost phase for today's ICBMs is rather long (several minutes) but could be shortened drastically on future ICBMs. Bus tracking requires a different sensor than booster tracking, since the bus plume

is much less conspicuous, and the bus rocket motor may not operate continuously. The bus is a target of declining value as it dispenses its RVs. Interruption of bus operation would not prevent the bus and its contents from continuing their ballistic flight to the target country, though the aim might be very wide of the target. Operating above the atmosphere, the bus can deploy lightweight shields, decoys, and sensor countermeasures (e.g., corner reflectors). On the other hand, x-ray lasers and neutral particle beams that cannot penetrate the atmosphere can attack the bus in space.

Anti-SLBM. A number of schemes have been suggested for using directed energy weapons against SLBMs, besides the obvious extensions of ICBM defense. Thus pop-up x-ray lasers could be positioned on U.S. coasts or ships at sea to intercept SLBMs launched from nearby Soviet submarines. Aircraft patrolling coastal waters and carrying lasers could attack ascending SLBMs in their area.

Anti-IRBM. Intermediate range ballistic missiles **(IRBMs) have short boost phases and potentially low trajectories, making anti-IRBM defense rather different from anti-ICBM defense and perhaps better accomplished with ground-based terminal BMD systems deployed in the theater.**

Defense of satellites ***(DSAT).*** Low-power wide-divergence (small optics) laser satellites (perhaps HF for high specific energy) could serve as "escorts" for other satellites, defending the other satellites from hostile objects—mines, ASAT missiles —approaching within a given range.

Anti-aircraft. At least four schemes have been broached for using directed energy weapons against aircraft or cruise missiles. The most ambitious would involve a worldwide constellation of trackers (possibly LWIR) and beam weapons (possibly DF or short wavelength lasers) to attack Soviet Blackjack strategic bombers, Backfire bombers attacking U.S. aircraft carriers, Soviet airborne command post "Doomsday planes, " Soviet AWACS radar planes, and so on. In a second scheme, B-1 or B-52 bombers would be outfitted with lasers (possibly DF) to protect them from Soviet fighters, surface-to-air missiles (SAMs), and air-to-air missiles. **A** third scheme equips carrier battle groups with lasers or particle beams to defend themselves against cruise missile attack. Fourth and last, ground-based beam weapons might replace surface-to-air missiles for local air defense.

Midcourse and terminal BMD. Intense electron beams have long been studied as replacements for interceptors in reentry BMD. In midcourse BMD, beam weapons might not only destroy RVs, but aid discrimination of RVs from lightweight decoys: lasers, particle beams, or x-ray lasers would illuminate approaching objects, and sensors would use the response of each object as an extra piece of data to judge whether it was a true RV (see Section 6).

Submarine communications. This scheme would use a blue-green laser to communicate with submerged submarines. Seawater is opaque to all but VLF and ELF radio frequencies, **used for submarine communications today, and to the blue-green portion of the visible light spectrum.** A blue-green laser beam originating on a satellite, reflected from a space-based mirror, or carried by an airplane **would be modulated** in accordance with the message to be transmitted and directed at a given spot on the ocean. After transmission **of the** full message, the beam would dwell on a neighboring spot and transmit again, and so on, eventually covering all submarine patrol areas. Optical sensors on the submarine hull would detect the message.

Blinding sensors and seekers. Analysts have studied a wide range of tactical applications for lasers, involving blinding of battlefield sensors, missile seekers, and even human beings.